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CHANGES IN THE GLACIERS OF MT RUAPEHU IN 1955

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Summary

Evidence is presented from moraines and historical records of the wasting and retreat of the glaciers of Mt. Ruapehu before 1955. The changes are compared with those on the Hooker and Mueller glaciers in the Southern Alps.

The summers of 1955 and 1956 were unusually warm at Mt. Ruapehu, and there was accelerated wasting and retreat of the glaciers, especially Whakapapa Glacier. Volcanic ash deposited on this glacier a few years earlier was exposed and spectacular dirt-cones developed beneath it.

WASTING ON RUAPEHU GLACIERS BEFORE 1955

Official contoured maps of Mt. Ruapehu and the surrounding region on a scale of 1 to 25,000 are being prepared from air photographs, but only the Rangipo sheet has been published. The accompanying sketch-maps of the glaciers (Fig. 1 to 3) are therefore based mainly on air photographs. The Rangipo sheet, however, includes parts of the Whangaehu and Mangatoetoenui glaciers, and provides data for measuring changes in those glaciers in the last 15 years, for although the map was printed in 1945, it was prepared from air photographs taken in 1941.

From 1941 to 1954 the Whangaehu Glacier retreated approximately 120 metres, and its loss of area was about 7·2 acres (1·8 ha.). There was also a small but notable change in drainage. In 1941 both snouts of the glacier emptied into the "gorge" (see "old outlet", Fig. 1). The

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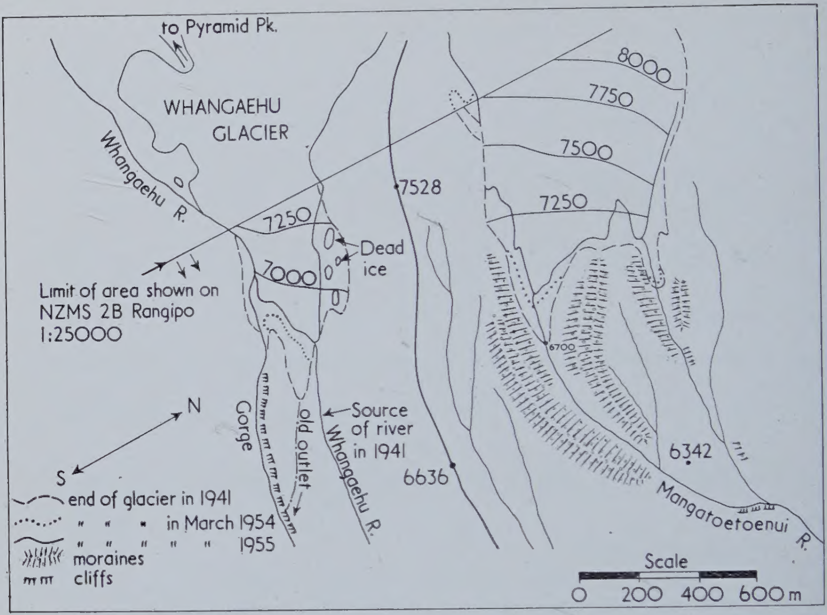

FIG. 1.—Sketch map of Whangaehu and Mangatoetoenui glaciers.

source of the northern branch of the Whangaehu River was a small lake some 250 metres from the present end of the glacier. The old outlet is now completely dry.

The main branch of the Mangatoetoenui Glacier retreated the same distance, 120m, but the northern branch retreated only 20m (Fig. 1). The loss in area amounts to approximately 6·8 acres (1·7 h.a.). Several sets of old moraines are aligned with the course of the streams emerging from the glacier. The most clearly defined lateral moraines follow the southern bank of the stream down to a point 750m from the present terminal face of the glacier. An "intermediate" stage is indicated by a set of moraines which converge at a point some 300m from the present terminal face. Several lateral moraines, though less clearly defined, occur in the northern branch of the Mangatoetoenui stream. It is possible that the valley between the two main streams was, at some stage, filled by a third branch of the glacier. Much farther down, at the confluence of the two main streams the steep, eastern banks show signs of glacial erosion, which indicates that during the maximum advance in recent times the Mangatoetoenui Glacier probably extended at least 1250m farther down the valley. Figure 1 also shows that the loss in area during the summer of 1955 was greater than the loss during the previous 15 years.

On the Mangaehuehu, the southern glacier of Ruapehu, the old moraines are very clearly defined (Fig. 2). In good weather they are

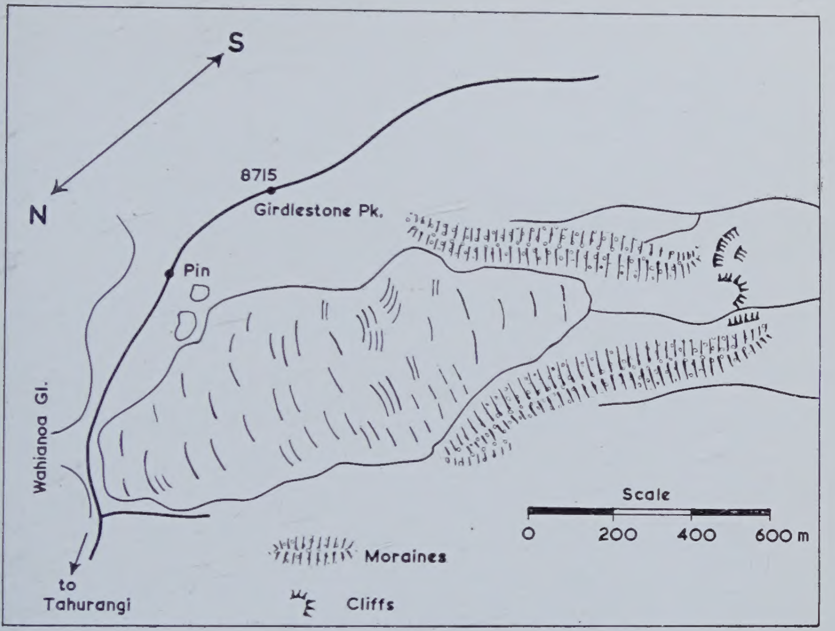

FIG. 2.—Sketch map of Mangaehuehu Glacier.

clearly visible from Wanganui, 55 miles away. The lateral moraines form sharp ridges, which rise up to 100m above the surface of the present end of the glacier and can be traced for some 500m downstream where they converge to form terminal moraines that are partly washed away. At the time of maximum advance the glacier ended in a small gorge just beyond these moraines. Several poorly defined moraines between the gorge and the present terminal face record stages in the retreat.

On the other glaciers of Ruapehu, moraines were not readily formed or preserved. The southern end of the Whangaehu Glacier lies in a narrow gorge where all the deposited material must have been carried away quickly. There are indications of some moraines following the "old outlet" of the northern branch of the Whangaehu Glacier but further investigation would be necessary to define their extent.

The scarcity of moraines along the Whakapapa Glacier can be explained by the peculiar shape of its basin. To the west the glacier is bordered by low walls, normally only emerging 10 to 30m from the glacier basin. The eastern side consists in its upper part of the rim of the North Crater, just projecting above the ice. If an increase in thickness of about 20m at the time of maximum recent glaciation is assumed, then most of the rocky wall to the west must have been covered by snow and ice. To the east there was probably a continuous ice-slope from the Summit Plateau to the Whakapapa Glacier. At that stage debris could only be supplied to the slopes near the terminus of the glacier. The basin of the Mangaturuturu shows a somewhat similar formation which explains the scarcity of moraines there.

The area of the Wahianoa Glacier which drains the south-eastern slopes of Ruapehu, was not visited. Air photographs taken in March 1955 show fairly large areas of dead ice, indicating a considerable shrinkage in area. The northern part of that glacier is shown to be completely separated from the main glacier.

The age of the moraines of the Mangatoetoenui and the Mangaehuehu is difficult to assess; in appearance they are very similar to the 1850 moraines of the European Alps. Unfortunately there is not much historical evidence. Ruapehu was first closely studied by Friedlaender (1899); subsequent accounts are not helpful, and nearly all are restricted to the northern glacier, the Whakapapa.

COMPARISON WITH SOUTH ISLAND GLACIERS

Harrington (1951) has discussed the age of the lateral moraines which accompany for miles the course of the Hooker, Mueller, and other Southern Alps glaciers. He considered that the size of trees formerly growing on the highest lateral terminal moraine of the Mueller Glacier suggested that it might date back to at least 1741, but could be much older. McKellar (1955) also studied the moraines of the Hooker and Mueller glaciers, and divided them into four groups. The oldest and highest set he called Group 1, which Harrington considers to be at least 200 years old. There is very little doubt that the clearly defined moraines of the Mangatoetoenui and the Mangaehuehu correspond to McKellar's Group 3, which formed about 1890. The signs of glacial erosion along the Mangatoetoenui Stream mentioned above, and some traces of plant-covered moraines in the Mangaehuehu area, might correspond to either Group 1 or Group 2 of the Hooker Glacier. It is, however, unlikely that fluctuations of the glaciers followed the same pattern in the North and South Islands for they were not uniform even in the South Island (Harrington, 1951). Glaciers of the Rakaia Valley, for example, began to recede in 1865 (Gage, 1951), whereas wasting on more southerly glaciers was not noticed until much later.

A photograph of the eastern side of Ruapehu, taken by Mr Denton of Wanganui in 1890, shows clearly that recession of the Mangatoetoenui must have started a considerable time before that date. The Whakapapa is the best known of all the glaciers of Ruapehu. Most of the visitors who intend to climb the mountain via the usual route from the north, pass the snout of the glacier. Messrs T. Latham and W. Mead of Wanganui, who have frequently climbed Ruapehu during the last 25 years, state that (pers. comm.) "this glacier was more or less stationary during that period. There were minor fluctuations, but no major retreat up to 1955." This accords with evidence from the other glaciers to indicate that there were no great changes in the glacierization of Ruapehu in the 20 or 25 years before 1955, in contrast to some of the glaciers of the South Island, where the Franz Josef Glacier (an atypical example), retreated nearly 1000m between 1933 and 1946 (Suggate, 1950, 1953).

WASTING OF WHAKAPAPA GLACIER IN 1955

Accelerated changes took place in the summer of 1955, when the Whakapapa Glacier appears to have been affected more than the other glaciers.

TABLE 1.—Positions of the Snout of the Whakapapa Glacier.

Year	Advance	Retreat
1954	2m*	
1955		94m
1956		65m
1957		6m
1958	stationary	

*Since 1952.

From 1952, when measurements were started by the writer, to 1954, the end of the glacier was more or less stationary. At the beginning of February 1955 it had receded 68m, two months later another 26m, a total of 94m in one year. This is a very considerable amount for such a small glacier (length 1·7km), but the shrinkage in area was far more impressive (Fig. 3). Large areas of rock emerged nearly every day, which shows both how surprisingly thin the glacier was and how fast the downwasting occurred. Wide *randklufts* (radiation troughs) separated the glacier from the rocks on both sides, so that it was difficult to get on to the glacier. It is difficult to estimate the amount of downwasting. Only at two places, at two rocky islands emerging from the glacier surface, was it possible to measure it fairly accurately. There the ice surface was lowered from 6 to 8m, but both places are in a marginal position; they do not give a full picture. Higher up, vertical downwasting is estimated to have been some 10 to 15m. Finsterwalder (1954) stated "that during the years 1920 to 1950 the surface of the glaciers of the European Alps was lowered, on the average, 0·61m per year." A downwasting of 10m on Ruapehu in 1955 would therefore be equivalent to 16 years of downwasting in the Alps. Normally the surface of the Whakapapa is surprisingly smooth, and there are hardly any crevasses. At the end of the summer of 1955 the surface of this glacier was so heavily creavssed that it was quite impossible to follow

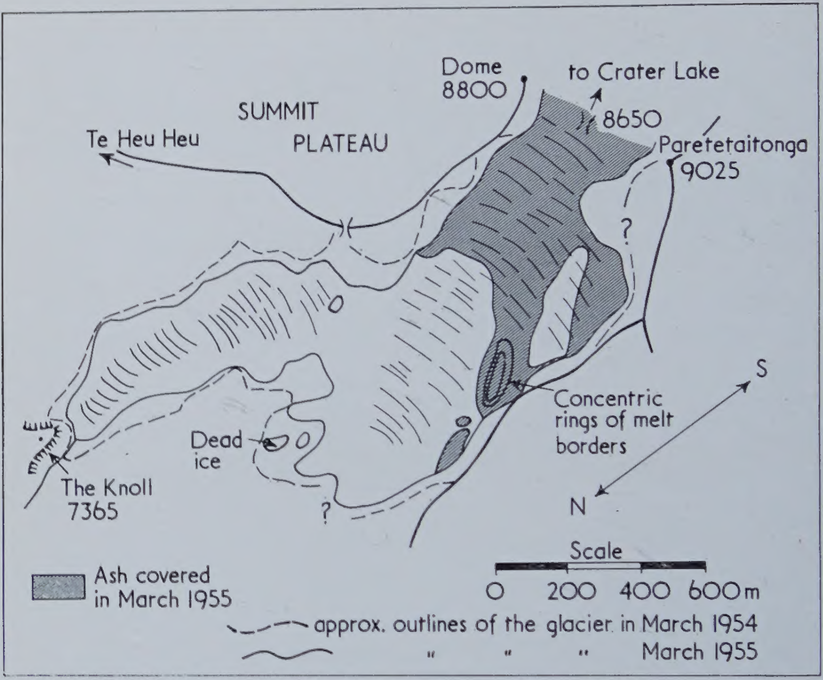

FIG. 3.—Sketch map of Whakapapa Glacier.

the usual route over the glacier to the Crater Lake. The breaking up of the surface had begun in January and by then the firn line had risen beyond the level of the highest summits. By mid-February there were many open crevasses, most of them still narrow enough to be easily negotiated. Nearly every day new ones opened up and the old ones became wider, commonly stretching right across the glacier. Most of them were not deep; they seldom exceeded 10m. Near the saddle the crevasses, although not deeper, reached down to rock and ground moraine. The glacier had become so thin, that its relatively brittle surface carapace rested directly on underlying rocks, and suffered fracturing and accelerated ablation, as happened earlier on the Godley Glacier in the Southern Alps (Harrington, 1951).

DIRT-CONES

Perhaps the most surprising phenomena in February 1955 were the hundreds of dirt-cones which dotted the surface of the Whakapapa Glacier. They were quite regularly arranged, mainly in parallel lines along the crevasses, more rarely at right-angles to them (Fig. 4). Nearly all were in the upper half of the Whakapapa, above 2300m, but not beyond 2550m, in areas where the glacier was still covered by ash. Their

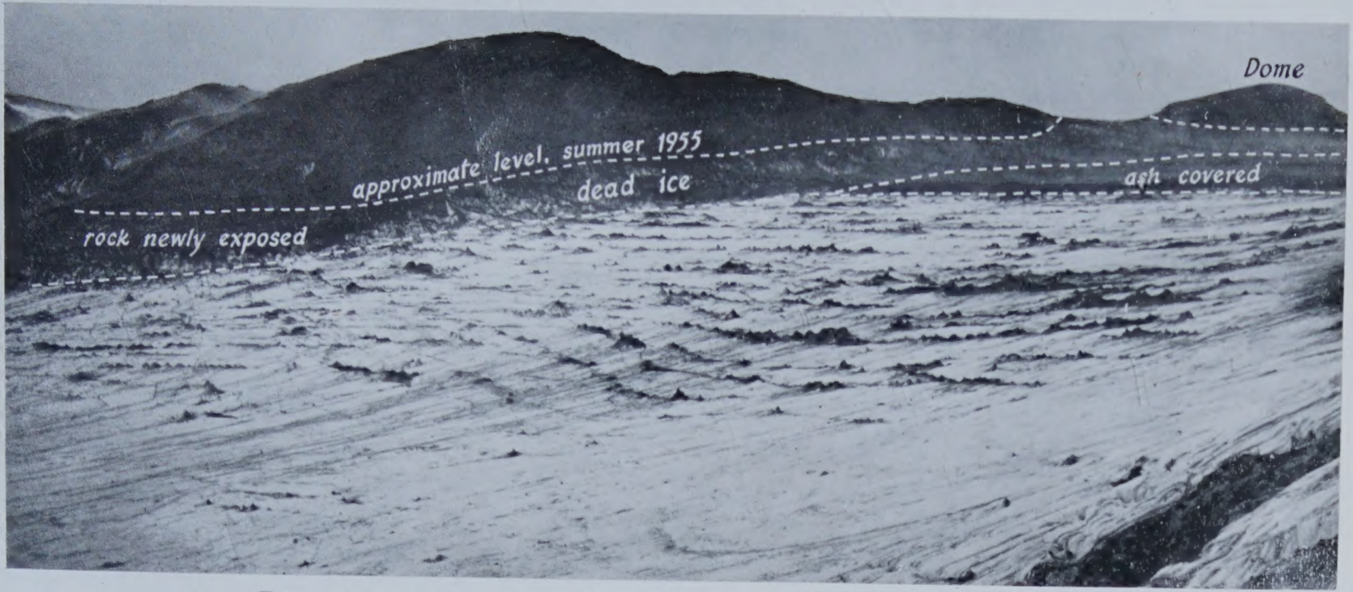

FIG. 4.—Lines of dirt-cones on the upper Whakapapa Glacier, 15 February 1955. View towards ridge from Dome (farthest right) to Te Heu Heu. Dead ice and newly exposed rocks (left) show the enormous amount of downwasting in summer 1955.

average height was about 2m, but they ranged from 50cm to 5m. All consisted of an ice core covered by a layer of black ash 5 to 7cm thick. Most of the dirt-cones presented, therefore, a similar picture to those of Skaftarjokull in Iceland described by Swithinbank (1950), but were somewhat steeper, the angle of their sides being 45 to 55°. They did not show a V-shaped groove at the apex of the ice-cone.

The formation of these cones has been discussed in detail by the writer (Krenek, 1958). Some, aligned along transverse crevasses, resulted from the deposition of ash in the crevasses by small streams of meltwater draining higher ash-covered portions of the glacier. Protection of immediately underlying ice by the ash resulted in development of the cones (Krenek, 1958, figs 1, 2, 3, and 5). Others, oriented at right-angles to the crevasses, represented the sites of parts of ridges of residual ash which had escaped transport by meltwater, and had become discontinuous and relatively slightly elevated by the opening of crevasses (Krenek, 958, figs 2 and 4).

The protective ash was supplied by the ash layer of the 1945 eruption of Ruapehu, and some possibly also by the 1949 and 1954 eruptions of Ngaurohoe. As a result of the enormous downwasting in the summer of 1955, the ash layer was exposed by mid-January.

In the later part of the summer, erosion played an increasingly important part in the shaping of the glacier surface. This was especially noticeable in the area between the summit plateau and the Whakapapa Glacier. There, the melt-waters cut deep gorges into the ice, leaving fantastic ice ridges, and pyramids standing between them. By headwards erosion these streams cut off ever increasing semi-circular areas from the ash-covered ice of the plateau, revealing at the same time the structure of the ice filling in the North Crater (Fig. 5). As the surface of the plateau was lowered, the rim of the North Crater emerged nearly everywhere. Finally, connections between the two ice masses were severed completely and huge ice pyramids were left stranded on the lowest saddles of the rim of the crater.

Equally great changes took place in the area around Crater Lake. The steep ice cliff bordering the northern side of the lake, which was

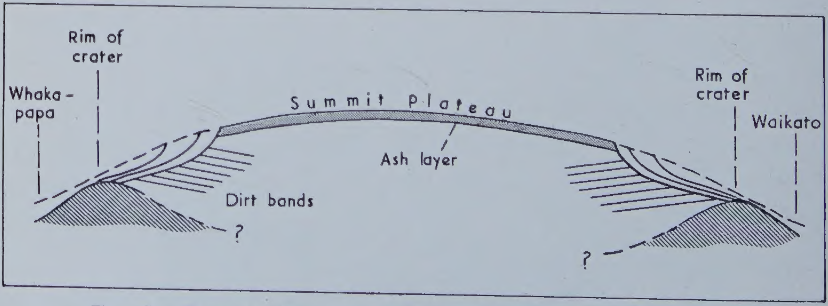

FIG. 5.—Cross-section through the North Crater of Ruapehu.

up to 30m high, disappeared completely. There is now a gentle slope from the saddle between Pare-te-tai-tonga and the Dome down to the Crater Lake. Against expectations, the level of the lake did not rise after the outbreak of 24 December 1953 (O'Shea, 1954); on the contrary, it had dropped 3 ft by May 1955.

CAUSES OF ACCELERATED WASTING IN 1955

Figure 6 showing temperatures and rainfall at the Chateau Tongariro (height 1060m), 4 miles from the end of the Whakapap Glacier, indicates that several factors were responsible for the unusually great recession and wasting of the glaciers of Ruapehu in 1955. June 1954 was considerably warmer than usual, so that very little snow accumulated except at the highest levels. July and August were about normal, though the rainfall was considerably above average. September and October, when much snow is normally contributed to the glacierized area, were very dry, October one of the driest on record. November was the warmest for over 50 years, except 1923. Ablation started,

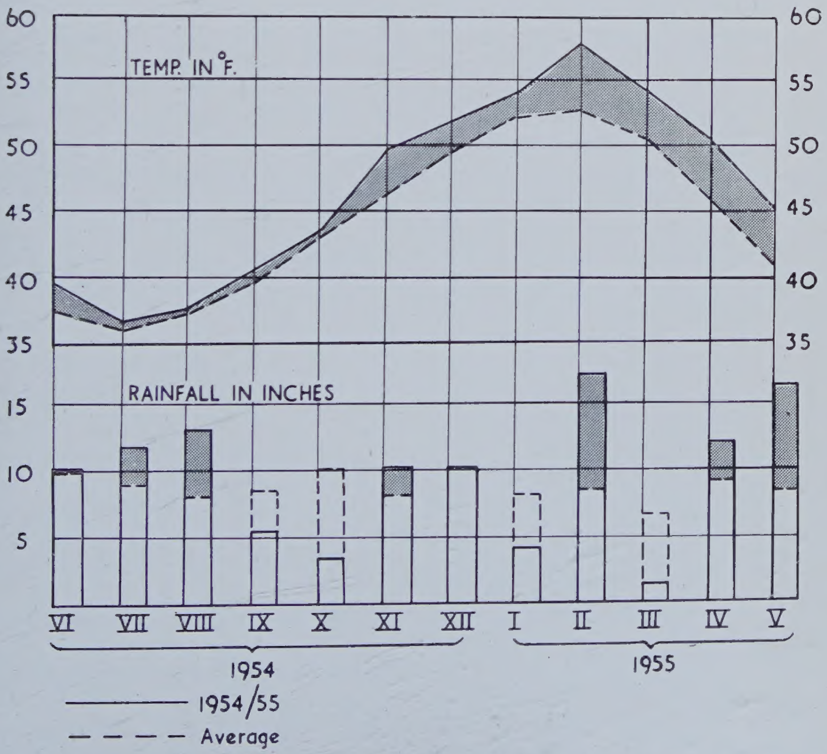

FIG. 6.—Temperatures and rainfall at Chateau Tongariro, June 1954 to May 1955.

therefore, at least a month earlier than usual at high levels. From November 1954 until April 1955 temperature were above normal all the time, 3·5° F higher on the average. February and April were 5° warmer than usual. The frequent showers in February, accompanied by high temperatures, hastened the decay of the glaciers.

Summer temperatures in 1956 were again considerably above normal (average above normal 2·2° F, Nov. 1955 to April 1956). However, as more snow accumulated during the winter months of 1955, the layer of ash was not exposed before the middle of February and the development of dirt-cones consequently started much later. All the glaciers of Ruapehu lost again in area and especially in volume, although developments were not as spectacular as in 1955. A tremendous amount of ash was washed down from the summit plateau to the upper Whangaehu. Most of that area was covered by a deposit up to 2 ft thick. At the end of the 1956 summer the Whakapapa Glacier was cut into two parts by a ridge emerging from under the ice. The north-eastern part is now completely cut off from its former sources of supply, the Summit Plateau and the collecting basin of the upper Whakapapa. It may disappear completely.

Conditions in 1957 indicated that the amount of snow accumulating during winter is the most important factor influencing the behaviour of the glaciers of Ruapehu. There were unusually heavy snowfalls, especially in August and, although summer temperatures were again above normal (average above normal 1·3° F), most of the glaciers were entirely snow-covered even at the end of the summer, so much so, that the positions of the snouts of some of the glaciers could not be determined. Curiously enough, on the uppermost part of the Whakapapa, ice emerged as early as mid-February. There was, so to say, an inverted firn line; the area above 2500m was free of snow, whereas the glacier below that line was snow-covered. This stresses the important role of wind on this isolated mountain.

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GEOLOGICAL STRUCTURE AND VOLCANISM OF THE TAUPO-TARAWERA DISTRICT

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Summary

The structure and volcanism of the Quaternary volcanic belt in the North Island of New Zealand are discussed in the light of geophysical evidence. The two major structural features outlined by the gravity survey are the Kaingaroa Plateau, in which the Mesozoic basement rocks are above sea-level, and the Taupo-White Island Depression, in which the basement reaches depths of at least 12,000 ft. Between the two are basement blocks at various stages of subsidence. These features can be closely correlated with surface topography, which indicates recent structural evolution; there is also evidence for a genetic relation between the hydrothermal fields and basement faults.

The distribution of volcanic rocks is shown by magnetic surveys; apart from the ignimbrites, these rocks are concentrated in the structural depressions; the dacites and andesites occur over partly subsided basement blocks, whereas rhyolites appear in the deepest depressions. This suggests an andesite-rhyolite sequence of volcanism, repeated as subsidence has progressed from one part of the area to another. A hypothesis is put forward to account for the appearance of the basalt in very small quantities. Although this does not explain the underlying causes, it correlates most of the observed features of the Taupo volcanism and suggests some factors responsible for the different types of volcanism here and on the West Coast of the North Island.

Introduction

The importance of geophysics in the study of New Zealand's structure and volcanism has long been recognized. At the instigation of Dr A. L. Day, of the Carnegie Institute Geophysical Laboratory, Washington, and of Sir Ernest Marsden, then secretary of the New Zealand Department of Scientific and Industrial Research, magnetic surveys of the hydrothermal fields began in 1937. But geophysical work received little further impetus until after the second world war, when a rapidly increasing demand for power called for greatly accelerated hydro-electric construction. Field parties have surveyed twelve hydro-electric projects in the Central North Island, using all the major geophysical prospecting techniques. Almost without exception, there have been problems of stability of the dams and leakage of the impounded water, posed by abandoned river channels choked with volcanic debris.

During the same period, the North Island hydrothermal fields have been examined as an alternative source of power. The harnessing of natural steam for power generation was successfully accomplished as long ago as the beginning of the century at Larderello, and for many years hot water has been piped into Reykjavik for heating purposes. But, lacking the added incentive of Italy's chemical wealth in the hot-

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spring waters or Iceland's harsh climate, New Zealand has been slow to follow suit. Systematic study of the hydrothermal fields began at Rotorua (Modriniak, 1945a, 1949); but in 1949 a Geothermal Advisory Committee directed that operations should be concentrated in the Wairakei-Taupo area in co-operation with the Ministry of Works. Some details of this survey, which preceded the commissioning of New Zealand's first geothermal power station, were given by Grange (1955). Geophysical surveys were subsequently extended to Kawerau (Studt, 1958a), where industrial use is now made of natural steam; to Waiotapu, where a further power station is being contemplated; and to several other fields.

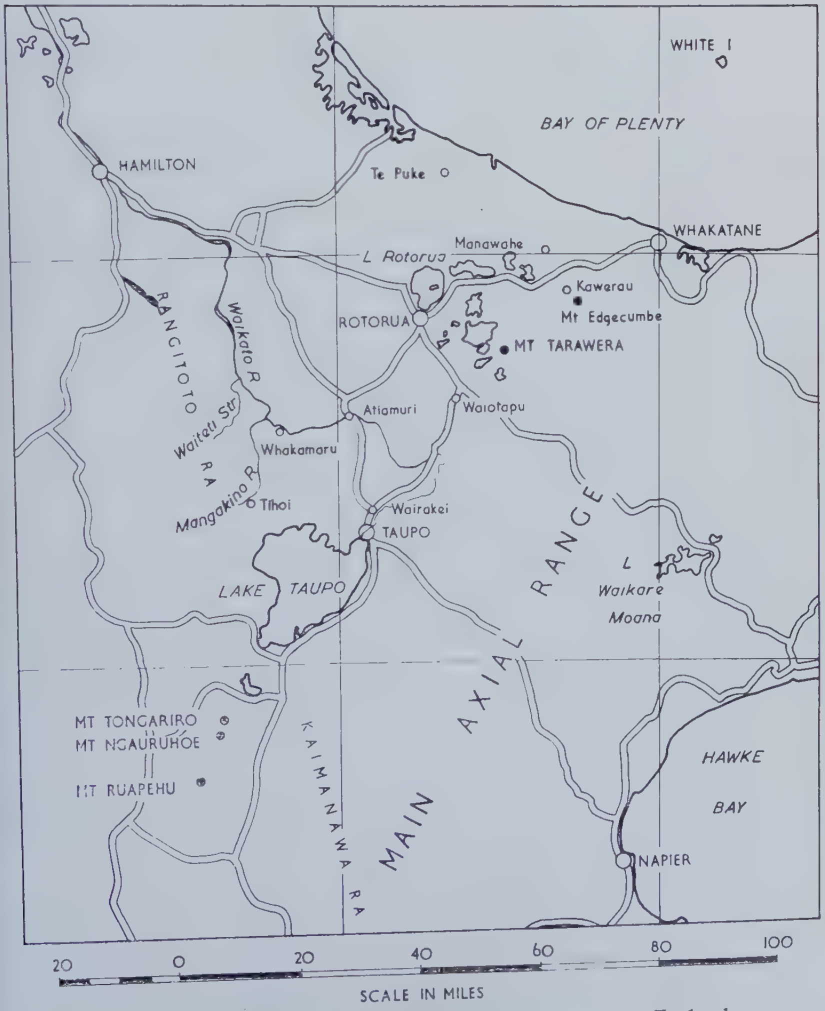

FIG. 1.—Locality Map: Central North Island, New Zealand.

Since a knowledge of regional characteristics is essential to the correct interpretation of some of the local surveys, both detailed and regional studies have proceeded hand in hand. In its bearing on structure and volcanism, the value of this work transcends the mere solution of engineering problems, and some of the information obtained is presented in this paper. Attention will for the most part be confined to a belt of country lying between Lake Taupo in the south and Mt. Tarawera in the north (Fig. 1). Consideration of broader aspects of the volcanic belt as a whole has been reserved for a subsequent paper.

Geology

Lake Taupo and Mt Tarawera are located in the centre of the North Island volcanic belt, which extends from Mt Ruapehu to White Island in the Bay of Plenty. White Island itself, and the three peaks Ruapehu, Ngauruhoe, and Tongariro are active volcanoes. Between Mt Ruapehu and White Island, the 1886 eruption of Mt Tarawera and a series of explosions at Frying Pan Flat (Morgan, 1917) are the only historic eruptions; but there are many youthful cones and domes (Kear, 1957), and carbon dating of volcanic ash and hydrothermal explosion deposits have given ages ranging from 4,000 to 800 years B.P. (Baumgart, 1954; Baumgart and Healy, 1956; Lloyd, 1959).

The hydrothermal phenomena are treated in this paper as an aspect of volcanism in general. Some hot springs are quite remote from any Quaternary or Late Tertiary volcanic environment (for example, Morere and Te Puia, on the Poverty Bay coast), and in the volcanic belt itself there is no indisputable evidence that the hot springs contain magmatic water. But the concentration of hot water in young volcanic provinces and the structural affinities of the two suggest a genetic relationship between hot springs and volcanism, so that a knowledge of one may promote an understanding of the other.

The general geology of the Taupo-Tarawera District, shown in Fig. 2, is based on the work of Grange (1937), who also gave salient details of numerous hot springs. Since Fig. 2 was drawn, a geological map of the northern part of the area has been published by Grindley (1959). This contains much detail not available in Grange's 1937 maps, and is therefore of more value for correlation with the geophysics, but it does not materially alter any of the interpretation made in this paper. Following previous authors, Grange developed the thesis that the volcanic belt occupies an extensive structural depression, which he named the Rotorua-Taupo Graben. Gravity surveys have confirmed the existence of a major depression, but it is a much more complex feature than Grange's term suggests; only its eastern margin is dealt with here.

The oldest rocks are Mesozoic greywackes, which make up the ranges east and west of the depression. These ranges were not formed at the same time, for Marwick (1946) states that uplift of the Rangitoto Range (in the west) was completed by Waitotaran time (Upper Pliocene) at the latest, whereas, according to Kingma (1957a, 1957b), the emergence of the eastern ranges (excepting Kaimanawa) did not begin

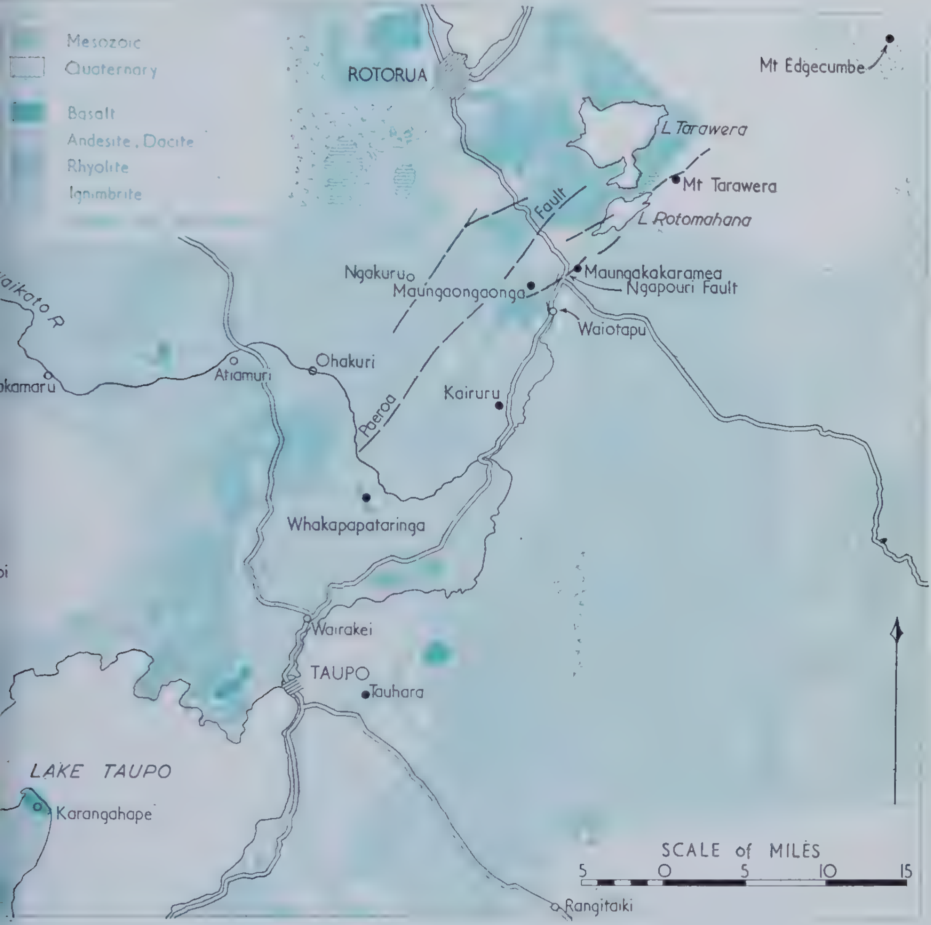

Fig. 2.—The geology of the Taupo-Tarawera District; mainly after Grange (1937).

until the Upper Waitotaran, and reached its climax only in the Upper Pleistocene. Within the volcanic belt also, the relative deformation of the ignimbrites gives reason to believe that structural evolution in the west antedated that in the east. It is assumed that the basement in the central depression is formed by the same Mesozoic greywackes that are seen in the ranges, though this has nowhere been proved; the exposed rocks are almost exclusively Pliocene to Recent acid volcanics. Extensive ignimbrites predominate, together with rhyolitic tuffs, domes, and flows. Dacite and andesite, though well distributed, are subsidiary, and there are a few isolated basalts, usually associated with large rhyolite masses.

Recent faulting is in evidence (Grange, 1932), and, as will be seen, there are other indications that structural development is still in progress. The volcanic belt closely parallels the "sub-crustal rift" defined by Eiby (1959) on the basis of earthquake epicentres, but there is a marked absence of focal depths less than 100 km (pers. comm., Mr G. A. Eiby).

Geophysical Survey Methods

All geophysical prospecting relies on contrasts in the physical properties of the various rock types—density, magnetic polarization, or seismic velocity, for instance. Some typical values for the rocks of the Taupo-Tarawera country are listed in Table 1.

It will be seen that there is a substantial density contrast between the Mesozoic and the younger rocks, with the exception of dacite, andesite, and basalt, which are of limited extent. The dominant factor influencing gravitational anomalies is therefore the thickness of younger rocks overlying the basement. For this reason, the initial interpretation of the gravity survey (Fig. 3) is made in terms of basement relief. It is obvious, however, that density contrasts within the cover also contribute to the gravity pattern; this is important in several hydrothermal fields, where igneous intrusions may control the movements of the hot water, but, since a gravity survey is incapable of unique solution without additional information from other sources, it is often impossible to assess the relative importance of this factor.

Whereas the gravity survey is related primarily to basement structure, the magnetic survey (Fig. 4) shows the distribution of the volcanic rocks within the cover, since the magnetization of most of these is more than ten times that of the basement rocks. The ratio of remanent to induced polarization (Q, or Koenigsberger factor) is high in many of the outcropping rhyolites, lower in the ignimbrites and the more basic volcanics, and very small in the non-welded fragmental rocks. Detailed mapping has depended largely on this ratio, for the contrast in susceptibility between the massive and fragmental rocks may be quite small, many of the so-called pumice breccias being tuffs, differing from the ignimbrites only in the absence of welding. Within the Taupo-Tarawera belt, there are no known examples of remanent magnetization not approximately conforming to the direction of the present earth's field.

Seismic refraction methods have been used to map the massive volcanics beneath a cover of tuff and alluvium, and reflection methods for studying structure in the layered sequences. Penetration is handicapped by poor shooting conditions in the loosely compacted pumice beds. The ignimbrites show great variation in seismic velocity, reflecting the variation in degree of welding; the poorly welded sheets cannot be distinguished seismically from alluvium or non-welded tuff.

Since the electrical resistivity of a rock formation varies with temperature, resistivity surveys have also been used in hydrothermal prospecting; a survey at Kawerau has been described (Studt, 1958a). The interpretation is complicated by porosity and salinity variations, and here again, the surface pumice beds are a handicap in that they give rise

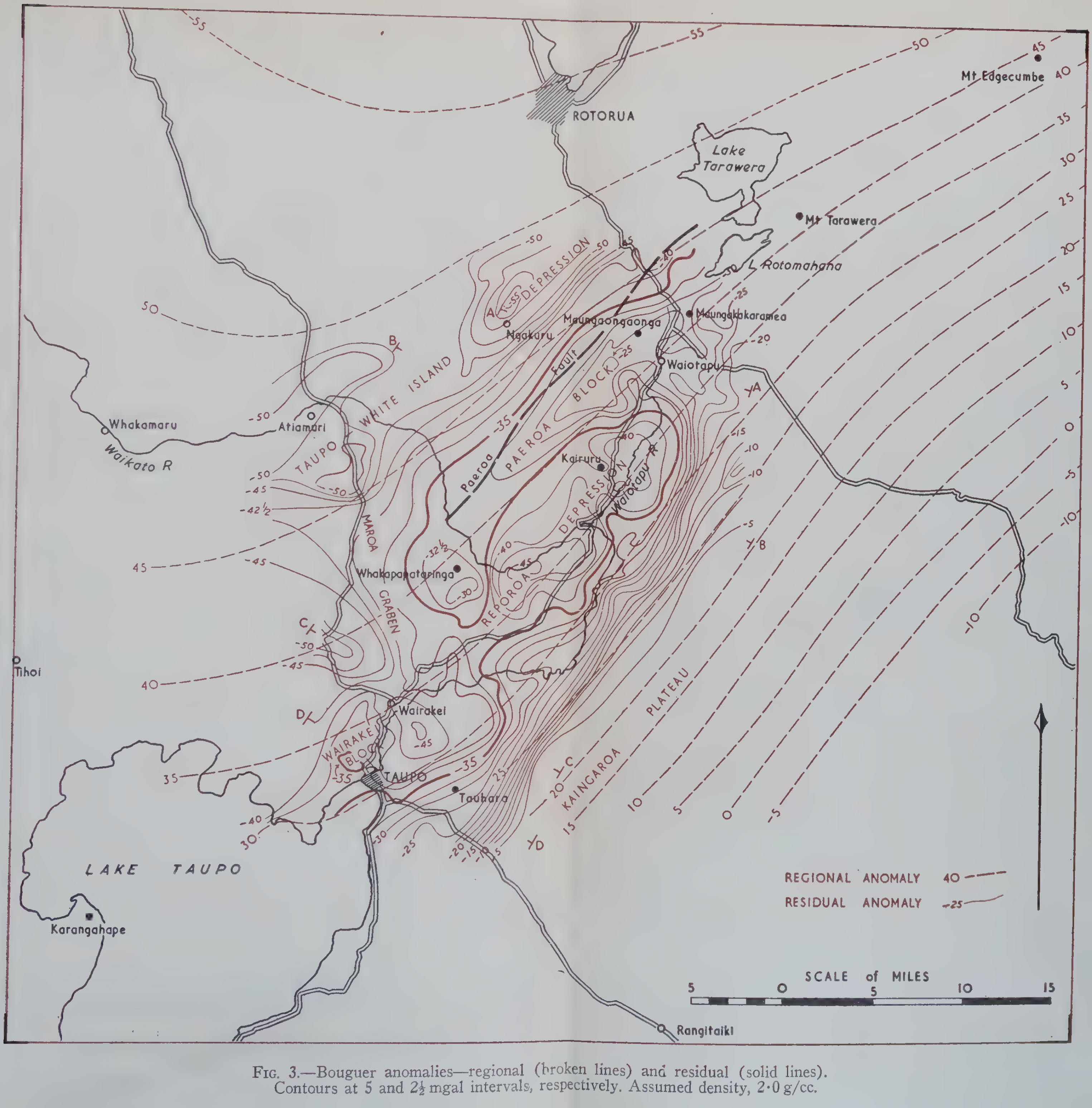

FIG. 3.—Bouguer anomalies—regional (broken lines) and residual (solid lines). Contours at 5 and 2½ mgal intervals, respectively. Assumed density, 2·0 g/cc.

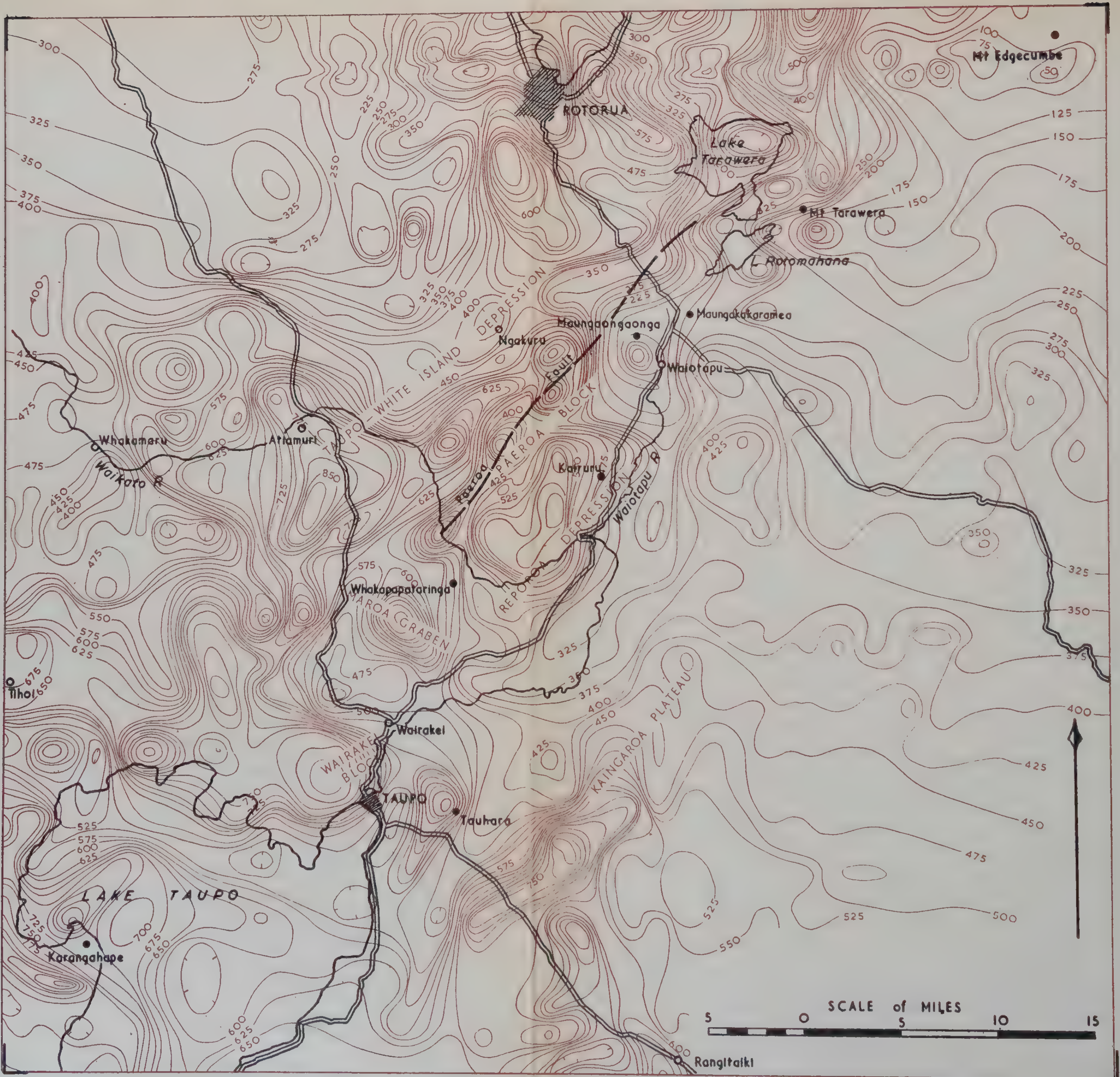

FIG. 4.—Total force magnetic survey at 5,000 ft above sea-level; based on the maps of Gerard and Lawrie (1955). Contours at 25-gamma intervals.

TABLE 1.—Physical Properties of the Major Rock Types.

Rock type	Saturated density g/cc			Magnetic susceptibility c.g.s units × 10−6			Remanent polarization c.g.s. units × 10−6			Seismic velocity (P-wave) ft/sec
	No.	Mean	Range	No.	Mean	Range	No.	Mean	Range	
Pumice tuff, breccia and sediments	29	1·77	1·51–2·08	29	310	0–1300	—	—	—	5,300– 7,500
Ignimbrite	66	2·21	1·58–2·54	66	690	35–1350	120*	2100	600–9400	5,300–10,000
Rhyolite	37	2·18	1·74–2·42	44	280	50–1100	10	2000	100–6060	7,000–12,000
Dacite	5	2·37	2·06–2·60	5	830	170–1750	2	150	100– 200	—
Andesite	2	2·47	2·41–2·53	2	1320	950–1700	1	1510	—	—
Basalt	7	2·79	2·64–2·90	7	2130	1100–3800	—	—	—	—
Greywacke	20	2·62	2·52–2·69	20	30	0– 80	—	—	—	12,000–14,000

*See also Hatherton (1954).

to very high contact resistances. Natural potential methods were tested and found to add little to existing knowledge of the hot springs.

GRAVITY SURVEY AND GENERAL STRUCTURE

Figure 3 shows a residual Bouguer anomaly map of the Taupo-Tarawera District, iso-anomaly contours being drawn at 2½ mgal intervals. The — 35 mgal contour conveniently indicates a number of structural features that are discussed in detail below, but it must be borne in mind that this contour does not exactly outline them. The survey was made with a North American gravity meter; elevation was usually measured by altimeter, and anomalies were computed to the nearest milligal. Practically all the stations were between 1,000 and 1,800 ft above sea-level. Station spacing was ½ to 2 miles, except at Wairakei, where ¼-mile spacing was used on some traverses. The Wairakei survey has been described by Beck and Robertson (1955).

In computing residual anomalies, the following corrections were applied: (1) free air, Bouguer and terrain (Hammer, 1939), using 2·0 g/cc as the density of all rocks above sea-level; (2) latitude, using the 1930 International Formula (Cassinis, 1930); (3) regional anomaly, extrapolated from stations on surrounding Mesozoic outcrops, where the greywacke density of 2·62 g/cc was used in reducing to sea-level. Regional anomaly contours are shown by broken lines at 5 mgal intervals in Fig. 3; they represent variations in gravity originating below the basement, and it is because these variations are abstracted that Fig. 3 is called a residual anomaly map.

The density of 2·0 g/cc used in the first correction is based on extensive surface sampling and a few drill cores. There is a wide variation in density, but this single value is used because the true density distribution is seldom known and cannot be inferred, as it can in sedimentary sequences. The main purpose of the survey has been to outline the broad structure, and the structural relief is such that small errors in density are not significant; but for a more detailed interpretation it should be noted that, at 1,200 ft above sea-level, a density error of 0·1 g/cc is equivalent to about 1½ mgal in the Bouguer anomaly.

Four cross-sections in Fig. 5 show the depth of the basement below sea-level computed from the gravity data, assuming a density contrast of 0·5 g/cc—that is, 2·62 and 2·12 g/cc for the greywacke and younger rocks respectively. The higher density here used for the cover reflects the compaction to be expected with increasing depth. However, at depths of several thousand feet it is quite possible that a still higher figure would be more appropriate; pumice is compacted at such depths and drilling has shown increase of density with depth in the ignimbrites and rhyolites (see also Martin, 1959). Reduction in density contrast implies greater depth to basement, and the depths shown in Fig. 5 (A–D) are therefore regarded as minima.

In the following paragraphs, where structural features are discussed, the terms plateau, depression, etc., refer to the basement and not to the surface topography, although the two reflect one another to some extent.

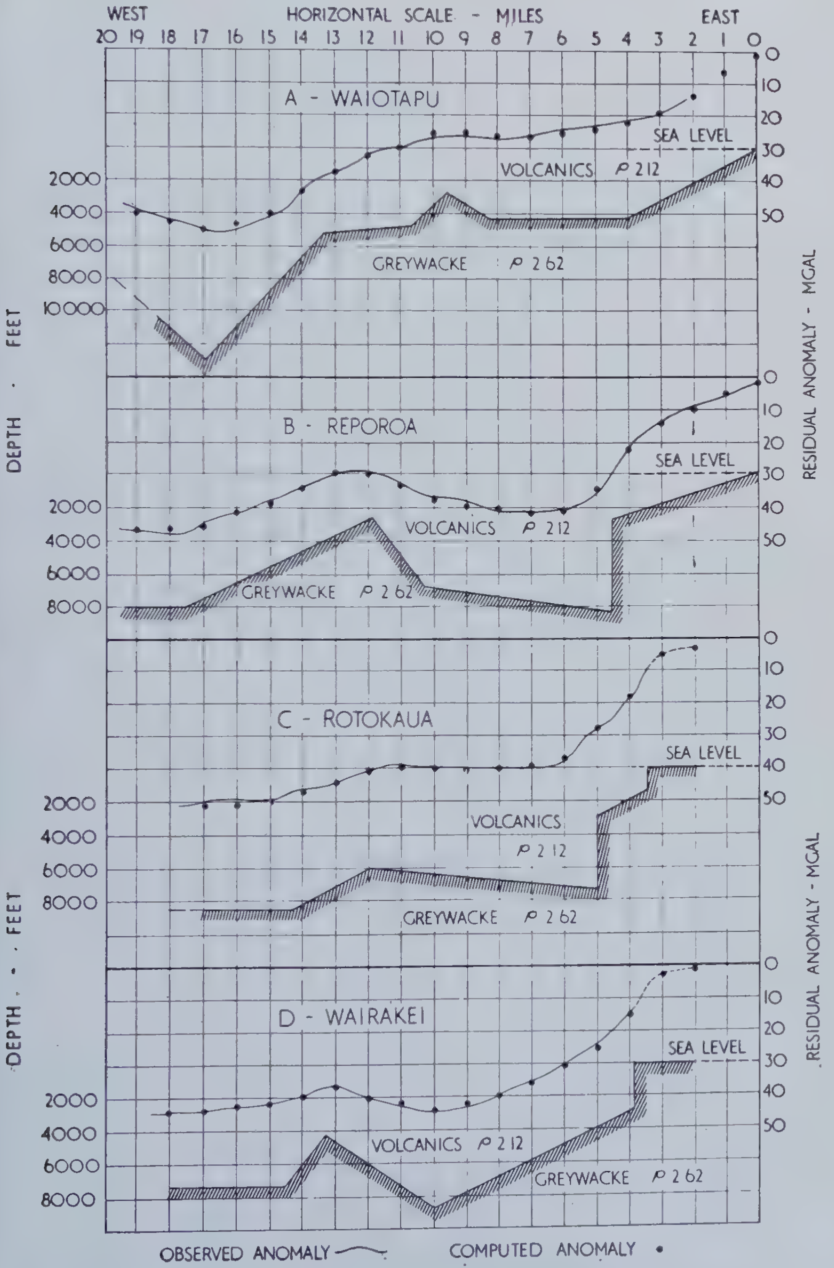

FIG. 5.—Cross-sections showing minimum depths to basement; computed from residual anomalies, assumed densities 2·62 and 2·12 g/cc in basement rocks and covering strata, respectively.

The Axial Range

The general alignment of residual anomaly contours in Fig. 3 is parallel to the north-north-east trend of the main Axial Range to the east. Robertson and Reilly (1958) pointed out that the southern half of this range is isostatically uncompensated, and from their map it appears likely that this applies also to the section adjacent to the volcanic belt.

The Kaingaroa Plateau

Westward from the Axial Range lies the Kaingaroa Plateau, which covers the south-east portion of Fig. 3. This is an ignimbrite plateau, but the gravity data indicate that the basement is above sea-level and generally not more than a few hundred feet below the surface. A few isolated Mesozoic inliers confirm this, also drilling and seismic work along the Taupo-Rangitaiki road. Thus the Kaingaroa Plateau is not merely topographical; it is a rather remarkable structural feature—a relatively undisturbed belt, 15 to 20 miles wide, separating the rugged, uplifted Axial Range from the depressed volcanic belt.

In many parts, the western margin of the Kaingaroa ignimbrite is marked by a scarp, and, because of its extent and linearity, Grange (1937, pp. 49–50) considered this to be a fault, although it is not shown as such on his maps. He named it the Kaingaroa Fault, and suggested that basement faulting would be continuous, even where the surface geology appears more consistent with warping.

Negative residual anomalies are recorded near the scarp, and they become increasingly negative westwards into the Reporoa Valley; this gravity gradient is prominent throughout the survey. In computed profiles (Fig. 3), it is interpreted in some places as basement faulting and in others as a quite gentle slope, but the available data do not permit this discrimination to be made with certainty, especially if step-faulting has been involved, or a buried fault scarp that was much matured before burial. Faulting is not unlikely, and along the Reporoa Valley its computed position is quite close to that of the ignimbrite scarp.

The Taupo-White Island Depression

Another structural concept introduced by Grange (1937, pp. 46–8) was the Rotorua-Taupo graben, although this was nowhere precisely defined. Gravity surveying outside the area here discussed has shown that the main depression is almost continuous from Lake Taupo into the Bay of Plenty, but Rotorua is located on a subsidiary structure, and the term Taupo-White Island Depression has therefore been introduced. Figure 3 shows a part of this depression, between Lake Taupo and Ngakuru; the indicated depth of the basement is more than 7,000 ft below sea-level throughout the greater part of the depression, and more than 12,000 ft below sea-level near Ngakuru itself.

As already mentioned, the true depths are probably greater than these. Moreover, at this distance, the validity of extrapolating the regional anomaly from a sedimentary into a volcanic province becomes more questionable, and this may also influence the computed depths. The solution to this problem of the true thickness of cover would be a most valuable contribution to the knowledge of the volcanic belt as a whole.

The Paeroa Block and Reporoa Depression

Between the Kaingaroa Plateau and the Taupo-White Island Depression is a southward-plunging structural high that coincides in part with the Paeroa Range. This is an ignimbrite range, but it is marked by low intensities on the aeromagnetic map described below, and the gravity anomaly is therefore interpreted as a basement high rather than volcanic mass. It has been named the Paeroa Block, and is regarded as partly subsided remnant of the Kaingaroa Plateau; at its highest point, it rises to less than 3,000 ft below sea-level. Grindley (1959) has recently used the term Paeroa Block in describing the surface geology, but, since the two entities so described coincide in all except depth, confusion should not arise, and the term is retained here.

From the Paeroa Range towards Reporoa, surface geology and seismic reflections show easterly dips, and the Paeroa Block is therefore interpreted as a tilted block rather than a horst. The Reporoa Depression may thus be regarded as a fault-angle depression along the Kaingaroa Fault. At Waiotapu, the Roporoa Depression appears to be cut off by a north-west fault, and the Paeroa Block and Kaingaroa Plateau are joined by a saddle, only about 4,000 ft below sea-level.

In Fig. 5 (A and B), the basement is shown dipping west from the Paeroa Block into the Taupo-White Island Depression, but the parallel Paeroa and Oteweta faults described by Grange (1937) (Paeroa, Te Weta, and Pouaiti faults of Grindley, 1959) show that step-faulting is actually present here. Farther north, these faults swing in a north-north-easterly direction towards the Kaingaroa Fault, terminating the Paeroa Block and Waiotapu Saddle.

It has been mentioned that the Paeroa Block plunges southwards; near Rotokaua (Fig. 5 C) the basement rises little higher than in the depressions on either side. But at Wairakei still farther south, Beck and Robertson (1955) reported a gravity anomaly which they termed the Wairakei High and interpreted as an elevated basement block (Fig. 5 D). This lies close to the trend of the Paeroa Block, suggesting that the two might be integral parts of the same structural unit. However, the gap between the two is an important structural feature, wider than it appears from the gravity survey, and it is discussed in a succeeding section under the heading Maroa Graben.

Minor Gravity Anomalies

Although the residual anomaly map has been interpreted in terms of basement relief, it is likely that much of the minor detail is due to density contrasts within the cover. One example is the narrow belt of high residuals cutting diagonally across the Reporoa Depression. It is unlikely that basement relief at a depth of 8,000 ft or more could cause this narrow anomaly; it is more probably due to volcanic rocks. This hypothesis is strengthened by the fact that Kairuru rhyolite dome lies in the centre of the belt.

Confirmatory evidence comes from a seismic survey in the Reporoa Valley. North of Kairuru, reflections were recorded from ignimbrites at depths of 1,000 ft to 3,000 ft; reflections were absent over the Kairuru belt, but were recorded again in one or two locations farther south. The loss of reflections is attributed to the existence of rhyolite, overlying the ignimbrite in the Kairuru area.

Other gravity anomalies associated with igneous rocks will be discussed later in this paper. These rocks must, as a rule, be rhyolite or andesite. Ignimbrite cannot be expected to alter the structural interpretation greatly, because the anomaly due to an infinite horizonal sheet is constant and independent of depth. This may explain why there appears to be little near-surface contribution to the anomaly pattern from such features as the Paeroa Fault.

Relation of Topography to Structure

The structure indicated by residual anomalies is closely reflected in the topography; for this reason geologists have from the earliest days had a good appreciation of the structure, despite the scarcity of stratigraphic clues. The plateaux are regions of high basement, and the main drainage basins coincide with the structural depressions, the outstanding example being Lake Taupo. This suggests that structural evolution has been active until very recent times, and may persist in present-day earth movements. Although only tentative correlation can be made at present between ignimbrites in the east and west sides of the volcanic belt, greater deformation of these rocks in the east suggests more recent structural development than in the west.

The course of the Waikato River is interesting. From Lake Taupo it flows north-east along the Reporoa Depression, escapes through the Maroa Graben to Atiamuri, and then traverses the largest gravity anomalies on its way to the foot of the Rangitoto Range, which it follows northwards (Fig. 1). In this northward course, there is a suggestion of strong structural control in the colinear courses of the Waikato and its tributaries Waiteti and Mangakino (more than 40 miles in length). It seems likely that the original drainage from Taupo took place over the Tihoi saddle and along this western course, but that progressive subsidence in the east eventually favoured the much longer course now followed. The diversion to the new course may well have been assisted by the choking of the old with pumice; there is abundant evidence of such events (Taylor, 1935; Healy, 1945; Thompson, 1958), and more than 250 ft thickness of current-bedded alluvium filling an old channel has been measured (F.E.S.) at the Waipapa dam site.

It is unlikely that the Waikato River ever continued north along the Reporoa Depression into the Rotorua Basin, as suggested by Cussen (1889), Hill (1905), and again by Beck (1951), because this would involve the crossing of the Waiotapu saddle, which is a structural as well as a topographical high. A course along the Taupo-White Island Depression would have been possible, but, again, the late structural development in the east makes the western course the more probable early outlet.

MAGNETIC SURVEYS AND THE VOLCANIC ROCKS

Aeromagnetic surveys over the volcanic belt were made by Gerard and Lawrie (1955). The interpretation of the maps was only briefly discussed, however, and, since it is of interest in the present work, a part of the main survey is reproduced in Fig. 4. This is a total force survey, flown 5,000 ft above sea-level, isomagnetic contours being drawn at 25-gamma intervals. Neither latitude nor regional corrections have been made. Owing to the profusion of magnetic rocks, their varying form and magnetization, and the consequent complexity of the magnetic field, the detailed interpretation of the aeromagnetic data is often difficult. Where detail is required, it has been the practice to make a ground-level survey with vertical force balances, as, for instance, at the Atiamuri dam site (Modriniak, 1951), where the Waikato River crosses a buried rhyolite dome. The value of the aeromagnetic map lies in its contribution to the structural picture when compared with the residual Bouguer anomaly map.

Three areas can be distinguished by their magnetic characteristics and correlated with structural features already described. Over the Mesozoic rocks in the east, the field is practically undisturbed, the normal latitude variation being the only significant feature. This is well shown by some of Gerard and Lawrie's profiles over the ranges and is to be expected in view of the weak magnetization of the greywacke indicated in Table 1.

Over most of the Kaingaroa Plateau, there is still no very great departure from the regular pattern, despite the high magnetization of many of the ignimbrites. The reason for this is that such rocks occur in continuous, uniformly magnetized sheets, which do not greatly disturb the regular magnetic pattern except at their edges. In addition, they are underlain at depths of a few hundred feet by virtually non-magnetic greywacke.

Steep magnetic gradients coincide with the position of the Kaingaroa Fault, and in the depressions farther west the field becomes highly complex. Although there are many anomalies which cannot be directly correlated with the suface geology, this complexity appears to be chiefly due to the rhyolitic rocks. Young andesite and dacite masses like Maungaongaonga, although highly magnetized, do not, as a rule, greatly influence the field at 5,000 ft above sea-level, showing that they are surface features with quite narrow roots.

The Wairakei Rhyolite

The rhyolites are mainly concentrated in the structural depressions, but there are one or two apparent exceptions, notably at the southern

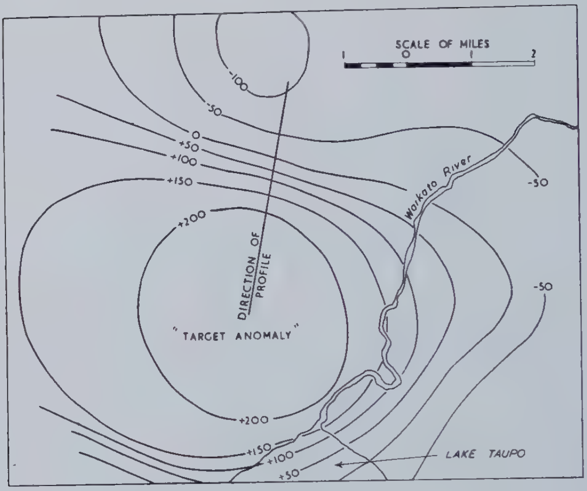

FIG. 6.—The "Target Anomaly", Wairakei. Total magnetic force at 5,000 ft above sea-level, showing profile analysed.

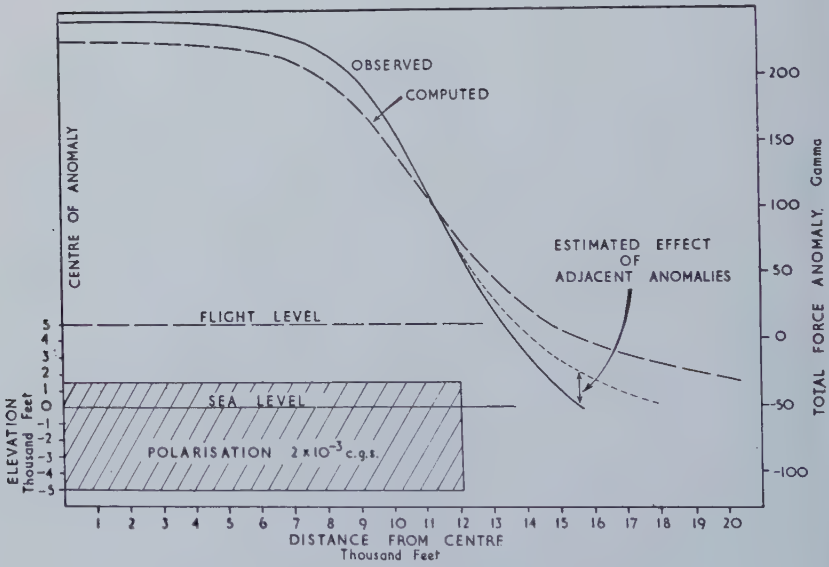

FIG. 7.—Interpretation of the magnetic "Target Anomaly".

extremities of both the Paeroa and Wairakei blocks. The so-called "target anomaly", south of Wairakei, reaches a maximum value of more than 300 gamma, and is associated with extensive rhyolite, capped at one point by a small flow of basalt. The basalt greatly influences surface observations, but its effect at 5,000 ft is negligible.

This anomaly was analysed by Mr C. E. Ingham; latitude and regional variations were abstracted and the field curve matched by theoretical curves for vertically polarized vertical cylinders. As shown in Figs 6 and 7, the best fit was obtained with a cylinder 12,000 ft in radius and 6,500 ft thick, with a polarization of $2{,}000 \times 10^{-6}$ c.g.s. units, which is close to that of the rhyolite.

No great accuracy is claimed for this result, especially since flow rhyolite is known to extend into the Wairakei hydrothermal field, well beyond the radius of the postulated cylinder. Nevertheless, the orders of magnitude are important, for this thickness of rhyolite, with a density of 2·25 g/cc in place of the standard 2·0 and 2·12 g/cc, would suffice to explain the southern half of the Wairakei gravity "high" without any basement relief. There is little doubt that at Wairakei itself there is basement uplift, but this is probably greatly diminished or entirely absent at the location of the target anomaly.

The Waiotapu Rhyolite

Two dacite cones (Maungaongaonga and Maungakakaramea) rise more than 1,000 ft above the surrounding country at Waiotapu, but have little influence on the magnetic survey. High intensities in this neighbourhood are associated with a much less prominent rhyolite dome two miles south of Maungaongaonga. Although partly the result of lower polarization of the dacite, this is also due to its superficial nature, as

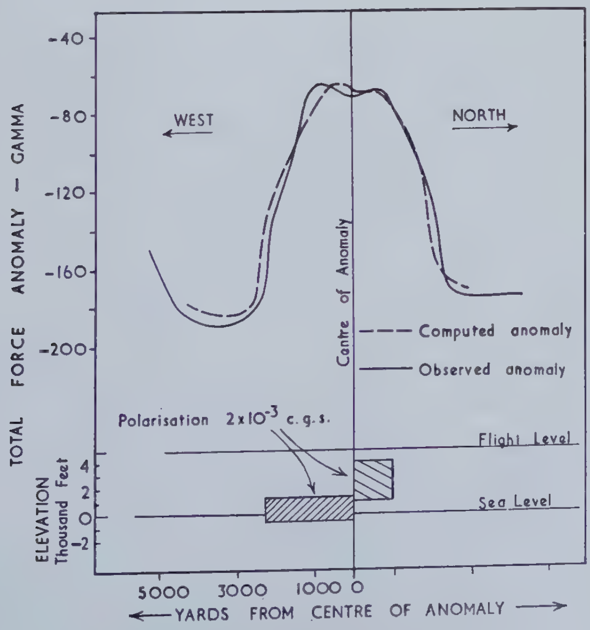

Fig. 8.—Interpretation of the Waiotapu magnetic anomaly.

shown by two drillholes which passed through this rock at shallow depth into ignimbrite and pumice breccia.

Mr Ingham's interpretation of the Waiotapu anomaly is shown in Fig. 8. A rhyolite body of the size indicated would cause a gravity anomaly of 2 or 3 mgal at most, and would not significantly modify the general structural interpretation. No gravity observations were made over the dome itself, but in Fig. 3 a small anomaly belt of this order of magnitude extends south-east from the dome and parallel to the faulting at the north end of the Reporoa Depression; it is suggested that this is due to buried rhyolite.

A perplexing feature is that, although there are good reasons for attributing such small gravity anomalies to igneous rocks, there is often little magnetic expression to support this interpretation. This may be due to lower magnetization of the deeper rocks than is measured in surface exposures. There is some evidence for this in that the polarization of core samples is usually below that of the same rock at outcrop. Since the difference is in remanence rather than in susceptibility, it is probably attributable to differences in thermal conditions at the time of emplacement.

The Maroa Graben

At the southern end of the Paeroa gravity "high" are the massive Maroa and Whakapapataringa volcanics; there is also an extensive magnetic anomaly. Analysis of this anomaly gives no simple solution comparable to the previous examples, but here, as at Wairakei, the gravity high is probably due to volcanic rocks. If this is so, then the actual gap between the Wairakei and Paeroa basement blocks is much wider than appears from the gravity data alone; it probably extends north from Wairakei to the Waikato River at Orakei Korako.

This gap is believed to be part of an important structural feature, here called the Maroa Graben, having the north-north-west trend of the Coromandel Peninsula. Henderson (1924) observed that the trend of the Coromandel andesite is continued southwards in the Kaimai Range, and its further extension towards Atiamuri is indicated by the distribution of magnetic anomalies. There is a suggestion of dextral offset at Atiamuri, but the Maroa Graben continues the same trend; moreover, on the maps of Gerard and Lawrie it can be followed right across the Kaingaroa Plateau to Rangitaiki, being marked by magnetic anomalies which are quite untypical of the plateau. As will be seen, the Maroa Graben appears to control much of the contemporary hydrothermal activity, and suggests continuity with hot springs along the flanks of the Kaimai and Coromandel ranges (Henderson and Bartrum, 1913). It is significant also that there are no hot springs or volcanoes throughout the length of the Kaingaroa Fault, except where the Maroa Graben intersects it at Mt Tauhara. Indeed, Grange (1937) singled out this sector as being one in which the Kaingaroa Fault is not in evidence, and the gravity contours are embayed here; both circumstances may result from cross-faulting.

It is not maintained that the Maroa Graben is a young feature, for the Coromandel structural trend is older than that of the Taupo-White Island Depression. Rather is it suggested that the Graben is an inherited line of weakness, and that volcanism in its various forms is therefore concentrated about the intersection of this line with the currently active structures. This explains the location of the Maroa volcanic centre, and also the points of origin of several recent ash showers, which, according to the results of isopach mapping by Baumgart (1954), lie on this same line just south of Tauhara (see Fig. 14).

The Hydrothermal Fields

Magnetic Prospecting

The earliest geophysical work in New Zealand's hydrothermal fields consisted of vertical force magnetic surveys. Wide reconnaissance was carried out by Watson-Munro (1938), who also traversed Mt Tarawera and made some of the earliest determinations of magnetic susceptibility. Jones (1940) examined Waiotapu and the southern shore of Lake Rotorua; Modriniak (1945b, 1949) extended the work in the Rotorua Basin and examined Awakeri, in the Bay of Plenty; Healy (1942) mapped the Tokaanu field. All these authors reported low magnetic intensities in hot areas; Watson-Munro and Jones attributed this to temperatures above the Curie point of the rocks (about 585° C), but the cause is now considered to be hydrothermal alteration of the ferromagnetic minerals.

Temperatures of nearly 600° C have been measured by Thompson in fumaroles on White Island (Rafter and others, 1958); it is impossible for steam at this temperature ever to have been in equilibrium with liquid water, but in other hydrothermal fields, water has always been found, except in local steam traps where gravity separation occurs. The temperature seldom rises far above the saturation value corresponding to the normal hydrostatic pressure, and the highest figure so far recorded was approximately 295° C at a depth of 3,200 ft at Waiotapu. Under this regime, the critical temperature would not be reached less than 7,000 ft below the surface, and the Curie point would be deeper still. These temperatures could occur nearer the surface only with abnormally high pressure, or in relatively impermeable rocks, which are rarely found above the basement.

On the other hand, the abruptness of the magnetic field variations at the margins of anomalous areas demands a very much shallower origin. Steiner (1953) has found plentiful evidence of the replacement of magnetite by pyrite, and of titanomagnetite by leucoxene and titanomorphite, and this alteration extends quite close to the surface.

The magnetic effect of this alteration was studied at Tikitere, 14 miles north of Mt Tarawera, where hot springs rise in water-sorted pumice sands overlying rhyolite of unknown depth. The surface waters are acid and much sulphur is deposited. The vertical force anomaly associated with the hot springs was found to be about —200 gamma, and the minimum polarization contrast required to give this is 350×10^{-6} c.g.s. units. The magnetic susceptibility of the unaltered rhyolite averaged about 250×10^{-6}, and Q was about 15, giving a total polarization of about $2{,}000 \times 10^{-6}$ c.g.s. units; thus the anomaly might be caused by an 18% drop in polarization. However, this treatment assumes that the rhyolite extends to great depth; if it is of limited thickness, the negative polarization at the lower surface cannot be neglected. The smaller the thickness, the greater is the degree of alteration required to account for the observed anomaly. Alteration of magnetite approaching 100% is often observed, so the rhyolite is probably not more than a few hundred feet thick.

The Source of Hot Water at Waiotapu

This field lies between the dacite and rhyolite peaks already mentioned in connection with aeromagnetic anomalies. A minor gravity anomaly at the south end of the field has been interpreted as an igneous intrusion. There is a second small anomaly at the north end of the field, along the line of the two dacite cones, and, although the cones themselves are known to be superficial, this anomaly may also mark an intrusive mass at greater depth.

Although hot springs and steaming ground are scattered over the intervening country, the concentration of the heat flow at the north and south ends of the field suggests a genetic relationship with these supposed intrusive bodies. It is postulated, therefore, that both the hot water and these bodies mark the presence of basement fractures. In the south, the presence of faulting is shown by the steep gravity gradient separating the Reporoa Depression from the Waiotapu Saddle; in the north, there is no geophysical indication of displacement, but there is close association of the hot water with the surface trace of the recently active Ngapouri Fault (Lloyd, 1959).

An alternative theory takes account of the fact that at Waiotapu the gravity "highs" practically encircle an area of lower values. This suggests a large caldera with the rhyolite and dacite peaks disposed around its rim, which is elsewhere buried beneath later tuffs and breccias. The hot springs are, of course, related to the volcanism which gave rise to the caldera. So far, drilling has failed to show much evidence of the chaotic tilting of collapsed blocks, which is commonly found in calderas. The two interpretations are not dissimilar; the former treats the encircling high gravity residuals as anomalous, whereas, according to the latter, it is the low residuals which are anomalous; the former ascribes the hot springs to two faults, the latter to general collapse.

The Source of Hot Water at Wairakei

The Wairakei magnetic survey, shown in Fig. 9, has an important bearing on the exploitation of the hydrothermal resources. It is a vertical force survey, iso-intensity contours being drawn at 50-gamma intervals relative to Wairakei absolute base (Cullington, 1954). The results

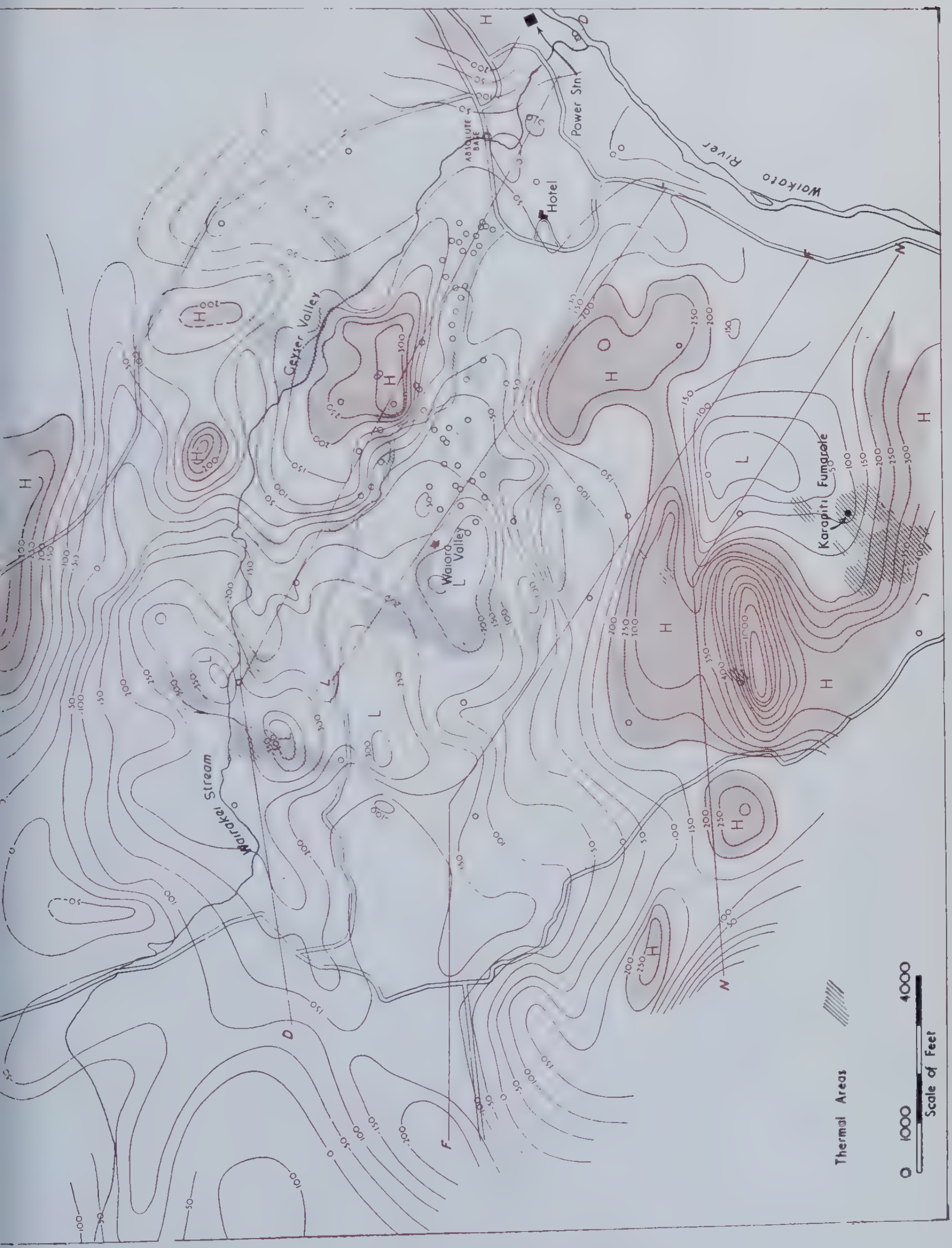

FIG. 9.—Wairakei; vertical force magnetic survey at ground-level. Contours at 50-gamma intervals relative to Wairakei absolute base (Cullington, 1954). Open circles represent drillholes.

are corrected for latitude, but not for topography, the effect of which over most of the survey is small.

The map is dominated in the south by the high intensities of the Target Anomaly, but a more interesting feature is the contrast between the low intensities covering the Waiora Valley and the western half of the field, and the high intensities surrounding Geyser Valley. To aid the study of this abnormal feature, a number of east–west traverses were run, and the results appear in Fig. 10. These profiles are disturbed in two places by steep-sided high-intensity zones, known from drilling and seismic evidence to be due to rhyolite; apart from this, each profile shows a drop of about 300 gamma over about 6,000 ft distance. Such a magnetic gradient might be due either to a progressive change in polarization close to the surface, or to a much sharper contrast at greater depth. The minimum contrast required would be about 500 $\times 10^{-6}$ c.g.s. units, and measurements on drill core samples showed values of only 100 to 200 $\times 10^{-6}$ in the top 1,500 ft of pumiceous sediments. For the deeper origin, a well-known formula (Nettleton, 1940) equates the depth to the centre of the magnetic contrast with half the

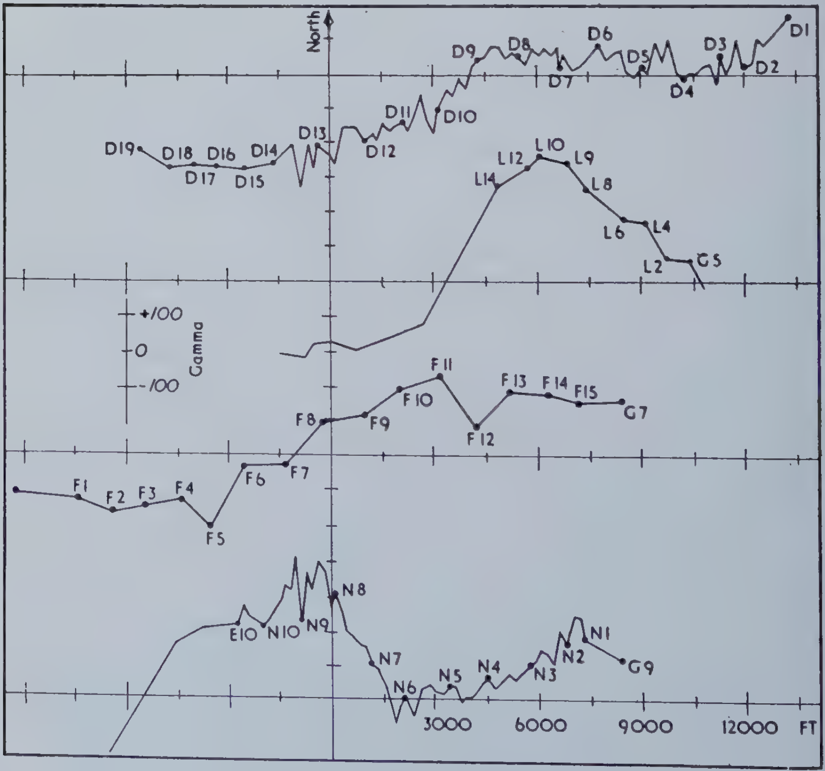

Fig. 10.—Wairakei; vertical force magnetic profiles.

separation of maximum and minimum intensities—that is, in the present example, about 3,000 ft. At this depth, a considerably higher polarization contrast would be required, and the presence of ignimbrite was therefore postulated.

Ignimbrite was subsequently proved by drilling to extend from about 2,000 to more than 4,000 ft in depth, and a sample from 3,200 ft was shown to have a polarization of $1{,}500 \times 10^{-6}$ c.g.s. units. There is little doubt that the polarization contrast is due to more widespread hydrothermal alteration of this ignimbrite in the west than in the east; a sample of ignimbrite, taken, not from the west, where no samples are available, but from the highly altered layers at the top of the formation, was found to have a polarization of only 280×10^{-6} c.g.s. units.

Whereas temperatures have been found to decrease with depth in the ignimbrite in that part of the field so far exploited, there is more likelihood of their continuing to increase through this formation in the west, since it is more altered there. The probable source of the hot water is thus in the west, and the majority of hot springs and drillholes are fed by percolation eastward up to two miles, above the ignimbrite and beneath a cap of Huka Mudstone. There is confirmatory evidence of this flow in the pressure distribution in the aquifer (Studt, 1958b).

A more detailed analysis of this work and its implications is presented by Studt (1959).

Seismic Investigations at Wairakei

Seismic refraction tests showed that high-velocity layers were not present within 1,200 ft of surface at Wairakei and Rotokaua. They also confirmed the essential continuity of rhyolite, at depths of a few hundred feet, between the Target Anomaly and the south-west margin of the Warakei field, where it was first located in drillholes. The rhyolite was found to have a rather variable seismic velocity.

Reflection work in the main Wairakei field was handicapped by the high natural noise level that commonly accompanies hydrothermal activity; tests were therefore shot farther south, along F and N lines of Fig. 10. The reflections were poor and discontinuous, and optimum shooting conditions varied unaccountably from one spread to the next. However, phantom horizons plotted on line F showed an anticlinal structure, conforming to the structural concept of the uplifted Wairakei basement block.

On line N, interval velocity data, together with shallow refraction results, gave the cross-section shown in Fig. 11. Pumiceous sediments make up the top layer, while both high-velocity layers and the intervening low-velocity layer correspond with rhyolite. This variation in rhyolite velocity, already noted in refraction work, was confirmed by well-shooting in hole No. 12. Its cause is not known, but might be associated with the attitude of the banding in this rock.

The most interesting feature of this work was the extremely low velocities indicated immediately below the rhyolite. These must be treated with some reserve, since they are based on measurement of small arrival-time differences on poor reflection records; nevertheless, five successive stations showed similar results. It is an established fact that seismic velocity is temperature-dependent; Fig. 12 shows curves published by Hughes and Jones (1950), which suggest that a 20% reduction in velocity might be expected at 200° C. However, in the present case, this can be no more than a contributory factor; many of the recorded velocities are much smaller than the minimum values normally

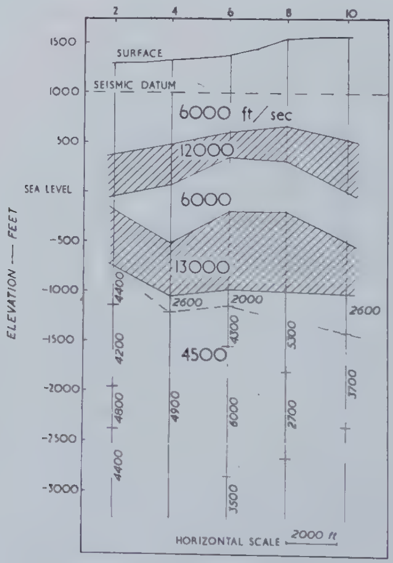

FIG. 11.—Wairakei; cross-section computed from seismic data, showing velocity layering.

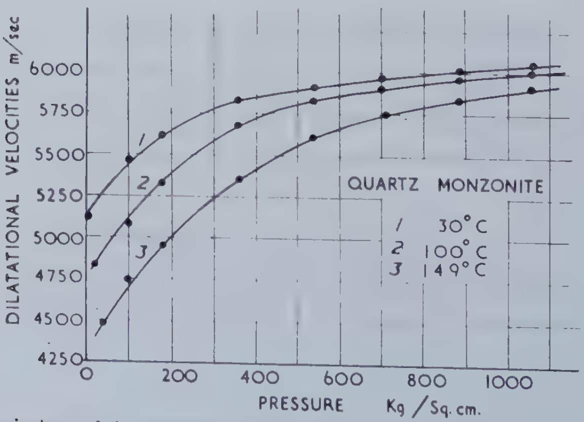

FIG. 12.—Variation of longitudinal wave velocity with temperature and pressure in quartz monzonite; after Hughes and Jones (1950).

recorded in water-saturated rocks (about 5,300 ft/sec), and if allowance is made for the usual increase of velocity with depth, the anomaly is still more pronounced. Very low velocities are often recorded above the water table, where air replaces water in the pore spaces of the rocks; beneath the Wairakei rhyolite, it was suggested that the same effect might be due to steam or gas, not necessarily in a single body, but disseminated in sufficient quantity to affect the seismic velocity.

The base of the rhyolite has recently been found by drilling at about 2,220 ft at the west end of X line; below this were 700 ft of pumiceous sediments and loosely welded ignimbrite, followed by further rhyolite. In the latter formation, the hydrothermal alteration was found to be as intense as any yet seen at Wairakei (Mr A. Steiner, pers. comm.), but temperatures have not so far proved as encouraging as the early seismic work suggested, the maximum value being about 236° C.

Seismic Velocities at Reporoa

A reflection survey was made in connection with hot springs in the Reporoa Valley. At the northern end of the valley, good reflections were obtained with 600 ft spread and 2,000 ft shot distance, by close control of the depth of shooting. The reflector, probably ignimbrite, dips east to south-east at about 10°. Strong natural filtering was encountered, frequencies being much higher on the pumiceous Pleistocene terrace gravels than in the low-lying marshy terrain.

The effect of compaction of the pumice tuffs on the longitudinal wave velocity is shown by curves of computed average and interval velocities in Fig. 13. Both split spread and reversed offset data were used.

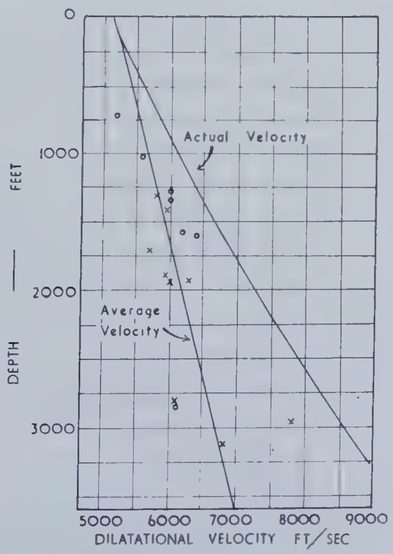

FIG. 13.—Reporoa Valley. Variation, with depth, of average and interval seismic velocities.

The Relation of the Hydrothermal Fields to Structure

The locations of the majority of the hydrothermal fields (Fig. 14) bear a systematic relation to the structure, since the hot water appears along basement faults. In some places, there is a very obvious association of the hot springs and fumaroles with surface fault traces, as, for example, at Waikite, Te Kopia, North Waiotapu, and Waimangu.

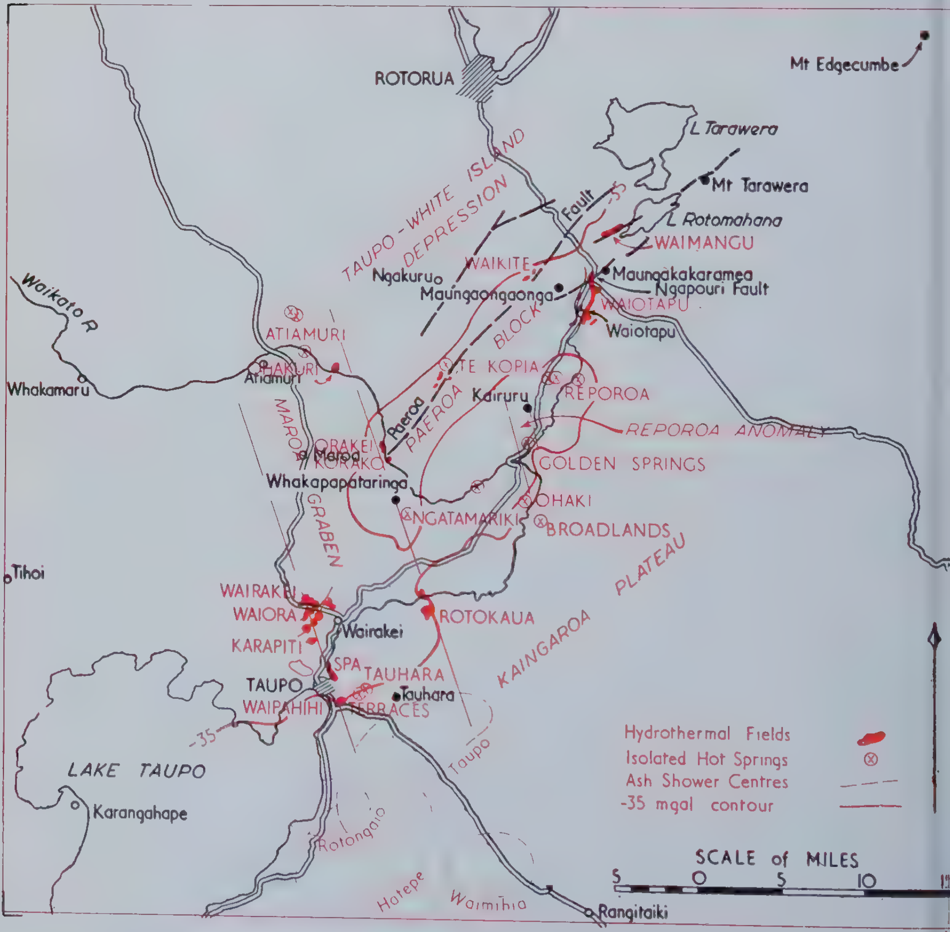

Fig. 14.—Relation of hot springs and ash eruption centres (after Baumgart, 1954) to the basement structure.

Elsewhere, there is evidence of superficial control of the hot water by minor faults, as Healy (1956) and Grindley (1957) have shown at Wairakei, while geophysics indicates a more fundamental association. Thus there is a remarkable alignment, along the east margin of the

Maroa Graben, of the Wairakei, Karapiti, Spa, Taupo, and Terraces hot springs, especially if the postulated western source of the Wairakei hot water is considered. There is a similar alignment along the eastern margin, of Rotokaua, Ngatamariki, Orakei Korako, and Atiamuri hot springs, and also of an almost extinct hydrothermal field at Ohakuri.

Elsewhere again, although there is little gravitational evidence of displacement, there is a suggestive juxtaposition of the hot springs and an elongated rhyolite mass, both probably related to the same basement fault. The outstanding example is afforded by Waimangu hot springs and Mt Tarawera; another is seen in Ngatamariki hot springs and the Whakapapataringa rhyolite. In some places, this association is less obvious, but a minor gravity anomaly suggests an igneous body, and therefore a basement fracture. Thus Broadlands, Ohaki, and Golden Springs lie along the Kairuru anomaly belt in the Reporoa Valley, and the Waiotapu example has already been described. Such rhyolite bodies probably contribute little to the heat flow, although they may, during emplacement, have opened up superficial fractures which now carry hot water (compare Einarsson, 1937, 1942).

The important factor is the association of both the rhyolite and the hot water with basement faulting. This association is considered to be sufficiently well established to be taken into account in any theory of origin of the hot wtaer. When this is done, it is difficult to reject, as did Banwell and others (1957, p. 22), the possible importance of deep circulation and conductive heating of meteoric water, such as Einarsson proposed in Iceland. Since basement fractures have recently given passage to fluid rhyolitic magma, it is possible that they still permit access of meteoric water to large areas of rock at high temperature.

On the other hand, the eruptions of the active volcanoes, the youthful form of others, and the young radio-carbon age assigned to many of the ash showers, all demonstrate that eruptible magma has very recently underlain much of the Taupo-Tarawera country; therefore, some magmatic steam contribution to the hot-spring waters is not unlikely. It is difficult to accept either origin without admitting the possibility of the other. Both probably operate, and connate water may also be present, as a result of regional thermal metamorphism of deep sediments. An observation by Wilson (1955) is pertinent. Comparing the chloride content at Wairakei with that of various magmatic waters, he finds that the magmatic contribution is unlikely to exceed 8%, whereas heat flow considerations indicate 25% (more recent data would accentuate the discrepancy). He concludes that magmatic steam cannot be the only heat source. The additional heat flow is probably conductive, the meteoric water being heated by the rocks before joining the magmatic water. Somewhat similar ideas have been expressed by White (1957).

However this may be, it is apparent from the geophysics that if prospecting for hydrothermal resources outside the known fields should ever be contemplated, then the search should begin along the established lineations, such as the Paeroa Fault and its branches, or the Maroa Graben.

SOME VOLCANOLOGICAL IMPLICATIONS

The Sequence of Volcanism

The concentration of rhyolites in the structural depressions has been mentioned; it suggests a genetic relation. The ignimbrites and pumice tuffs found on the plateaux are more mobile phases of the rhyolitic volcanism, and were probably also erupted from vents in the depressions. Cotton (1944) classed the depressions as volcano-tectonic collapse areas, due to the removal from below of the material furnishing the rhyolites. He pointed out that some of the ignimbrites must have been erupted in the early stages of the collapse, because they themselves have undergone subsequent deformation; since deformation (and presumably also volcanism) has migrated from one sector to another during the complex history of the volcanic belt, this is understandable.

The distribution of andesite and dacite is somewhat different from that of rhyolite; they are seen at the margins of the depressions, generally over partly subsided basement blocks, as indicated by the gravity survey. The location of the andesitic Mt Edgecumbe on a fault at the north end of the Kaingaroa Plateau has been described (Studt, 1958a); the dacitic Maungaongaonga and Maungakakaramea are located over the Waiotapu basement saddle. These three exmples are quite young; the dacitic Mt Tauhara is a rather older and more deep-seated example (Beck, 1951) at the intersection of the Kaingaroa Fault with the Maroa Graben, and Rolles Peak (Beck and Robertson, 1955) is older still. Thus the volcanism tends to be more basic where subsidence is least advanced, which suggests that subsidence progresses as rhyolite outpourings succeed andesitic or dacitic volcanism. It also suggests that some of the aeromagnetic anomalies recorded over the depressions may be related to earlier dacites and andesites, similar to those at Manawahe (Grange, 1937) and Te Puke (Bartrum, 1913). It is interesting to note that andesite has been encountered in drillholes over basement highs at both Wairakei and Waiotapu, where none appears at surface.

An andesite-dacite-rhyolite succession was recognized in the Coromandel volcanics by various authors (e.g., Henderson and Bartrum, 1913; Morgan, 1924), although it appears to have been repeated more than once. Grange did not recognize any such succession in the Rotorua-Taupo district, and it would be difficult to substantiate without the aid of geophysics. This is because there has been no single sequence throughout the area; there is, instead, a type sequence, that has been repeated from place to place as subsidence has proceeded, piecemeal, through the area. It seems less likely that it has been repeated in any one place, and apparent reversals, for example, the young dacite cones overlying ignimbrite at Waiotapu, may be due to the widespread inundation by the mobile acid rocks, of adjacent sectors at younger stages of development.

The Role of Basalt

The place of isolated basalts in such a sequence is not obvious. They are typically late eruptions, associated with large rhyolite masses in the structural depressions.

Steiner (1958) argued that the volcanic rocks of the Taupo suite fall mainly into a continuously variable series from basalt to dacite, the variation being due to crystal separation in a parental basalt magma, together with assimilation of metamorphosed sediments. The rhyolitic rocks, on the other hand, are attributed to the heating of the sediments by the basalt magma until eruptible rhyolite is produced. This appears compatible with the sequence postulated above; the lavas will become more and more acidic as assimilation and fractionation proceed, until the rhyolites erupt and collapse occurs.

Clark (in press) has elaborated somewhat similar theories of petrogenesis, but he has been more impressed by the scarcity of basalt exposures, and postulates differentiation in an andesitic rather than a basaltic magma, although the parental material was originally basalt. Clark describes the K Trig and Tarawera basalts as having tholeiitic affinities—that is, akin to basalts with world-wide distribution; it can therefore be argued that there is a "normal" basaltic crustal layer. But to judge from the regional anomaly contours shown in Fig. 3, this layer is probably abnormally close to surface—abnormally, at least when compared with the depth in the country to the east and south, for the regional anomalies decrease rapidly in these directions. For this reason, any theory of petrogenesis in which basalt plays a major role must, as Clark points out, give a convincing explanation for the fact that, despite extensive faulting, this basalt has been erupted so seldom and in such small quantities.

An explanation can be formulated on the basis of the simple hydrostatic theory of volcanism (see, for example, Holmes, 1944, p. 478), which, although it tells nothing of the underlying causes of the volcanism, yet co-ordinates most of the observed features.

A Mechanism of Volcanism

Suppose there is at some depth h_1 a layer of basaltic magma, or of basaltic rocks at such a temperature as will cause them to melt on reduction of pressure; it is unlikely that this basalt could be held in the liquid state, for its density would then be too low to account for the observed regional anomaly. Neglecting rigidity, the pressure in this layer is entirely due to the weight of the overlying solid crust; $p = d_1h_1$ where d_1 is the mean density of the crust. Now, if the crust is fractured, liquid magma will rise along the fault to a height, h_2, such that $d_1h_1 = d_2h_2$, d_2 being the mean density of the column of liquid magma. The excess head in the magma available to cause eruption is then given by

$$h_2 - h_1 = h_1(d_1 - d_2)/d_2$$

This is the height above the earth's surface to which the magma can rise. But if $d_1 < d_2$, there can be no eruption, unless it is promoted by vesiculation in the vent, which effectively reduces d_2. This is probably the situation in the Taupo-Tarawera district, for at K Trig., Tarawera, and elsewhere, the high ratio of scoria and lapilli to lava shows that explosive vesiculation was a major factor in the eruptions.

The density of molten basalt is commonly given as about 2·75 g/cc (e.g., Daly, 1933), and it is doubtful whether the mean density of the solid crust in the centre of the North Island would be as high as this. The evidence in favour of this is as follows: (1) the gravity survey and drilling have demonstrated the very low density of the uppermost layers; (2) the basement rocks exposed in the ranges to the east are of considerable thickness and mean density about 2·62 g/cc; (3) the rhyolitic volcanism itself indicates an abnormally high magma reservoir; (4) there is a regional negative magnetic anomaly, compatible with a high magma reservoir; this is seen in the anomaly map of Gerard and Lawrie (1955, map 6), surrounding the central positive anomaly that they attributed to the residual effect of the surface volcanics. Thus, although regional Bouguer anomalies suggest that basalt may be abnormally close to surface, there is evidence that the density of the crust overlying the basalt is abnormally low.

If conditions are as suggested, then most of the phenomena that are observed or postulated in the Taupo-Tarawera district follow quite naturally. There is a long-lived, but barely eruptible, basalt magma, with every opportunity for assimilation and differentiation until magma of andesitic composition and eruptible density is produced. There will be concordant intrusion, and great depth of sediment undergoing regional thermal metamorphism. Some connate water driven off in this process, together with some magmatic steam, may combine with conductive heating of meteoric waters to supply the hot springs. Further heating of the sediments will generate new rhyolitic magma, giving violent but short-lived ignimbrite and tuff eruptions, or quieter rhyolite extrusions, according to the volatile content. The associated subsidence would bring more sediments within the range of metamorphism and melting, and open new passages through which the andesite-rhyolite succession would again be propagated.

Concordant intrusion by rhyolite might also be expected, in view of the very light and unconsolidated nature of some of the near-surface deposits, and it is possible that some of the rhyolite flows reported in such sequences are, in fact, sills. The low angle of many of these bodies conflicts with the high viscosity usually attributed to this type of lava, if they are flows.

COMPARISON WITH OTHER CENTRES

Conditions on the West Coast of the North Island are obviously very different, although regional anomalies are again high. The known sediments are much more dense; the heat flow is smaller and magnetic anomalies are positive, so that any magma reservoir would be at greater depth. Basalt is therefore freely eruptible, there is less opportunity for heating of sediments, and indigenous rhyolite is absent. In the Tongariro National Park area, the presence of basalt and absence of rhyolite, together with the height at which andesite is erupted, suggest that conditions resemble those on the West Coast rather than those at Taupo. Sediments with a density of 2·75 g/cc have recently been discovered by Mr A. Malahoff in the National Park.

Kear (1959) has recently assembled some interesting data on the Cenozoic volcanism of North Auckland, Coromandel, and the West Coast, and he suggests that events in the Taupo volcanic belt may parallel those which have occurred to the north and west. Certainly, there are many similarities, but it would be a mistake to expect too close a correlation between adjacent volcanic provinces where there may be other factors militating against this, as Kear himself remarked.

Kear finds evidence of a general sequence from andesite, through dacite and rhyolite, to basalt, with deformation in the rhyolite phase and both southward and eastward migration of foci. If basalt is an essential late phase of the volcanic cycle, this can be dovetailed into the above hypothesis only by regarding the basalt eruptions as representing a period of declining volcanism, when the crust overlying the magma reservoir must now incorporate denser layers than before, including perhaps andesite and some of the basalt itself. It could then be suggested that the late basalt eruptions at Tarawera, K Trig., and elsewhere indicate a dying phase of the Taupo volcanism, or at least of one particular arc in the volcanic belt.

However, no basalts are reported from Coromandel, where the cycle was apparently completed with Pliocene rhyolite. Indeed, no rock type appears consistently in the sequence at all centres; at Auckland, for example, the only volcanic rock preceding Holocene basalt appears to have been andesite of Oligocene age, and at National Park, the current andesitic volcanism has associated basalts, but dacite and andesite are virtually absent.

It seems more likely that the andesite-dacite-rhyolite sequence should be expected only where sedimentary densities are low and the magma chamber is shallow; this sequence may therefore end without basalt, as at Coromandel, or with minor quantities only. Where sedimentary densities are high, and where the magma chamber is deep, the sequence might be andesite-dacite-basalt, or andesite-basalt, or even simply basalt, depending on the ease with which the basalt can be erupted. All these sequences are seen in various parts of the West Coast and the North Auckland Peninsula; all may have a common heredity—basaltic magma—the differences being due to contrasts in environment (though there may also be chemical differences which are hereditary rather than environmental).

If this is the way of things, then there should be no cause to anticipate rhyolitic volcanism in the National Park area, where basalt is eruptible. But in the eastern Bay of Plenty there are big positive regional and negative residual Bouguer anomalies (Studt, 1958a). This indicates a density distribution unfavourable to basalt eruption, and suggests that a more acid phase is likely to succeed the andesites of Mt Edgecumbe, and Whale and White islands.

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TE KUITI GROUP

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Summary

First usage of the stratigraphic term Te Kuiti is reviewed, with special consideration of restrictions in its use and of the upper limit of its application. Adoption of the name "Te Kuiti Group" is supported, and a revised definition proposed. Stratigraphical columns are presented covering an area from Papakura to Taumarunui. The constituent formations of the group are described, their type localities are recorded, and the following new formations are introduced: Mangakotuku Siltstone, Glen Massey Formation (including Elgood Limestone, Dunphail Siltstone, and Glen Massey Sandstone members), Waitetuna Limestone Member of the Aotea Sandstone, Te Akatea Siltstone, Orahiri Limestone, Otorohanga Limestone, and Mangapehi Sandstone.

Isopachs, shorelines, and facies distribution are described and illustrated. Short sections on facies control of faunas and geological history are also included.

Introduction

There has been much confusion concerning the precise definition of the stratigraphical term "Te Kuiti". Two separate problems are involved. Firstly, the original definition was applied to a sequence of rocks that would now be termed a group; but subsequent authors progressively restricted it to little more than formational rank. Part of this restriction was unsound, however, and a return to a wider definition that includes the lowest Tertiary beds is proposed. Secondly, it is claimed that the original field mapping was confused in part. It has thus become necessary to re-define the upper limit of the group to correspond to the top of the formation that has commonly been known as the "Te Kuiti Limestone".

The name "Te Kuiti Group" (Fleming, 1947, p. 108) is preferred to either "Te Kuiti Series" or "Te Kuiti Beds".

Sections exposed from Papakura to Piriaka, near Taumarunui (Fig. 1) are illustrated as columns A to P (Fig. 2, Table 1). The ages of the microfossil samples that are quoted in the text or in these columns were determined by Mr N. de B. Hornibrook (of New Zealand Geological Survey, Lower Hutt), who either made the original determinations or has brought up to date the determinations of the late Dr H. J. Finlay.

For convenience of writing, the paper has been divided into two parts. The first ("Rock Units", by D.K.) discusses the usages and definitions of "Te Kuiti Group", and defines the constituent formations, and the second ("Paleogeography", by J.C.S.) discusses the paleogeog-

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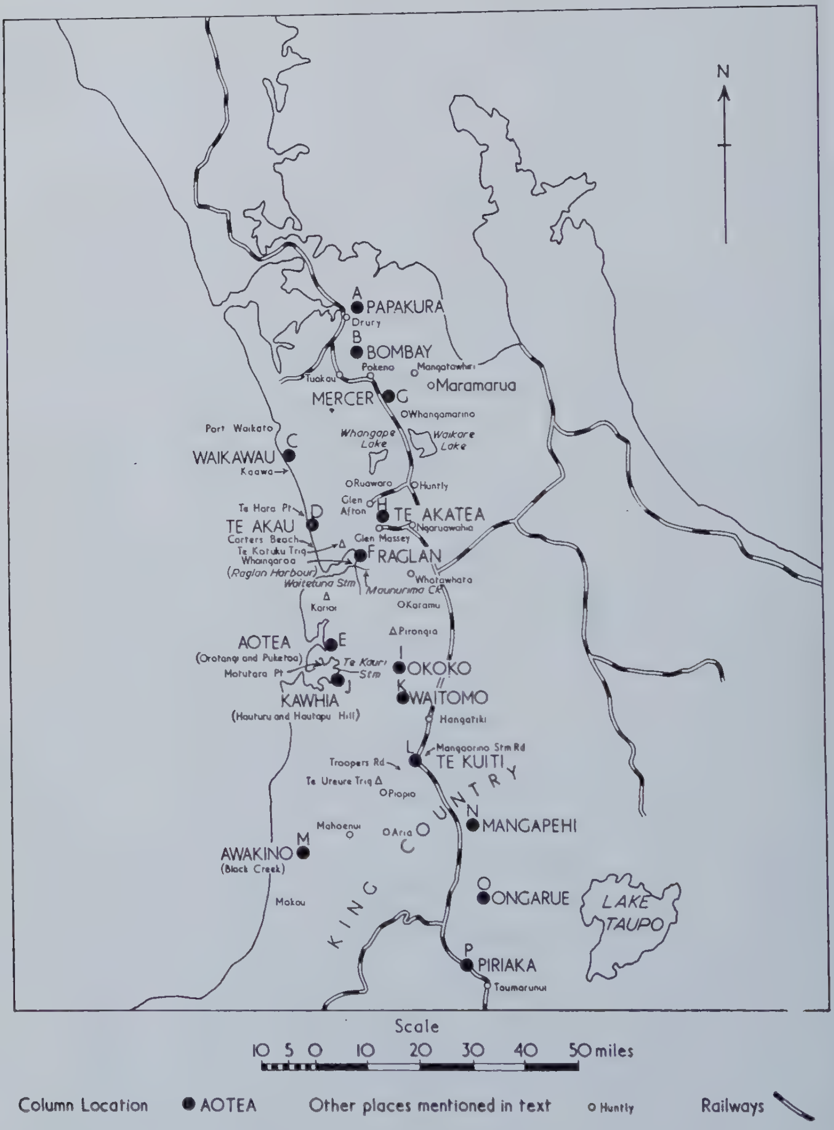

FIG. 1.—Map showing the locations of columns in Fig. 2, and all geographical names mentioned in the text that are not included in Figs 3, 5, or 7.

raphy and geological history, largely by means of isopach, shoreline, and facies maps. The fieldwork on which the paper is based has been carried out separately or jointly by both authors in the course of various surveys during the years 1949–57.

TABLE 1.—Locality and Other Details of Columns in Fig. 2.

Col.	Name	Locality data	Remarks
A	Papakura	Hays Stream, below Papakura-Hunua Highway, 2 miles east of Papakura (N 47/500338)	Papakura Limestone sample collected by Prof. A. R. Lillie
B	Bombay	Upper Hingaia Stream Valley (N 47/510221–527224)	See also Bartrum and Branch (1936)
C	Waikawau	From west coast to north and south of Waikawau Stream mouth (N 51/248864)	
D	Te Akau	Coast, 100 chains south of Rangikahu Trig. (N 55/327616)	Post-Te Kuiti faulting does not appear in the overlying beds. The latter beds contain limestone fragments and rest either on Otorohanga Limestone or Waitomo Sandstone (see Henderson and Grange, 1926, Plate 2, Figs 3, 4)
E.	Aotea	South-east coast of harbour, Orotangi (N 73/379199)	Type locality Aotea Sandstone
F	Raglan	North Shore Raglan Harbour and hills to north (N 55/394540–465551)	
G	Mercer	Cutting for Great South Road and Main Trunk railway in centre of township and in drillhole below (N 52/562082)	Only Po-Ph strata are exposed at surface, in which many samples are not shown individually
H	Te Akatea	Composite of "Te Akatea Section" (N 56/568664), and "Dunphail Bluffs", 4 to 7 miles west of Ngaruawahia (N 56/597647–603643)	See Figs 3, 4, 5 for detail. Type locality for Te Akatea Siltstone, and of Glen Massey Formation and Mangakotuku Siltstone
I	Okoko	Okoko Road, and hill exposures on Kawhia highway from there towards Te Rau-o-moa (N 74/581079–585102)	
J	Kawhia	Shellbed and coal at base of section from Dallys Mine (N 73/495083); the rest of the section from Hautapu Hill, Hauturu, and the road ½ mile east (N 73/446085–445088)	Large oysters form the bulk of the topmost part of the upper limestone

K	Waitomo	"Worths Quarry" (N 74/659967)	See Fig. 7 for details. Type locality of Orahiri Limestone, Waitomo Sandstone, and Otorohanga Limestone
L	Te Kuiti	A, from road between Te Kuiti and Trig. Pukenui (N 83/678789); B, from Troopers Road (N 83/609775); C, from Beros' Quarry, Te Kuiti (N 83/703790); D, from Mairoa Road (N 83/562770); and E, from Otewa Road, 6 miles north-east of Te Kuiti (N 83/779856)	Upper 40 ft of limestone in Beros' Quarry is extremely pure, and white in colour. Balance is somewhat sandy and blue-grey.
M	Awakino	A, from Black Creek basin (Awakino North S.D.); B and C, from old Awakino Road, ½ and ¼ mile respectively west of Stony Creek (Awakino East S.D.)	See text for detail of Black Creek section.
N	Mangapehi	Vicinity of Mangapehi Mine, Benneydale.	See Fig. 8 for detail; also Gage (1942)
O	Ongarue	Waione Stream, 10 miles east of Ongarue (Haurakia and Puketapu S.D.)	See also Kear (1952)
P	Piriaka	Railway cutting 4 miles south of Taumarunui, and bank of Wanganui River below (Hunua S.D.)	

ROCK UNITS

By DAVID KEAR

USAGE AND DEFINITIONS

Past Usage

The name "Te Kuiti" was first applied in a stratigraphic sense by Henderson and Ongley (1923), who used it in the Mokau Subdivision to identify the basal "series" of the Tertiary sequence. They stated (pp. 25–6) that the Te Kuiti Series was so named "from the presence about that town of thick massive limestone that is the most characteritstic rock of the series. . . . The beds below this rock cover only small areas, vary greatly in nature and thickness, are usually thin, and from many localities are practically absent. Where the underlying beds are thick, they consist for the most part of blue calcareous and arenaceous claystone. . . . Upwards, the limestone grades into blue claystone, everywhere calcareous and in places also arenaceous. In places . . . these claystones overlap the limestone and rest upon Mesozoic rocks. They are about 200 ft thick." In other passages, Henderson and Ongley gave the thickness of the limestone as ranging from 20 ft to 200 ft, and of the underlying beds, which locally include basal carbonaceous shale and coal, as up to 100 ft.

Henderson and Grange (1926), in describing the geology of the Huntly-Kawhia Subdivision, restricted the term "Te Kuiti Beds" to the youngest of the beds that had been included in the original definition of "Te Kuiti Series". For the older marine beds, they re-introduced "Whaingaroa", which (p. 46) "was first used by Hutton [1867] to designate the blue calcareous, sandy claystone outcropping at the eastern end of Whaingaroa or Raglan Harbour, and passing beneath the massive limestone prominent in that area". They used "Coal-measures" in a formational sense for the basal terrestrial sediments below their designated Whaingaroa Beds.

The Te Kuiti Subdivision was mapped in detail by Dr H. T. Ferrar and Messrs N. H. Taylor and J. H. Williamson during 1928–32. Williamson (1932), in a brief summary of the work, discontinued the use of "Whaingaroa"; but his small-scale map implied a new restriction to the "Te Kuiti Series" by transferring Henderson and Ongley's "uppermost calcareous and arenaceous claystone" to the overlying "Mahoenui Series". On the Mangaorino Stream Road alone, 2 miles north-east of Te Kuiti, was this bed mapped as "Te Kuiti", and, although it is thin and unconformably overlain by Mokau sandstones, there appears no valid lithological reason for making the exception. In his text, Williamson did not exclude this upper claystone (which will be referred to below as the "Upper Te Kuiti Claystone") from his description of the "Te Kuiti Series". He stated (p. 7): "The limestone is overlain by blue arenaceous mudstone containing shell fragments and Foraminifera", but he made no mention of a locality where it might be examined.

Gage (1942) divided the "Te Kuiti Series" at Mangapehi into an upper and lower part. His Upper Te Kuiti Series consisted of massive sandy mudstone of Waitakian age,* possibly 1,200 ft thick, and may be correlated with the "upper Te Kuiti claystone". His lower Te Kuiti Series comprised up to 50 ft of coal measures overlain by 150 to 200 ft of a "massive glauconitic sandstone" of Duntroonian age.

Marwick (1946) gave a detailed account of the 1928–32 fieldwork. He reinstated the Whaingaroa Series, but admitted that it could not be differentiated from the Te Kuiti in some areas. Where differentiation was possible, the Whaingaroa Series consisted of the coal measures and those marine beds that are below the typical Te Kuiti limestone.

The maps accompanying Marwick's bulletin referred the "upper Te Kuiti Claystone" mainly to the Mahoenui Series, although this bed was mapped as Te Kuiti on the Mangaorino Stream Road, and near Mangapehi Mine, where the 1928–32 mapping was amended to correspond to Gage's work. In his text, however, Marwick went further than Williamson by omitting all reference to the bed under the heading "Te Kuiti Series". In fact, he stated (p. 11), "the Te Kuiti *limestone* [our italics] is overlain by the Mahoenui beds, consisting typically of mudstone, though, locally, sandstone predominates".

Farther to the south, in the headwaters of Wanganui River, it has always been difficult to decide whether the basal Tertiary beds should be mapped as Te Kuiti or Mahoenui "Series" (Grange, 1930; Fyfe, 1945; Kear, 1952). The confusion is due mainly to the lack of precise definition of the stratigraphy nearer Te Kuiti township.

Proposed Limits of "Te Kuiti Group"

LOWER LIMIT OF GROUP

Henderson and Grange (1926) restricted the term "Te Kuiti" by the introduction of "Whaingaroa Beds" and "Coal-measures" for the lowest beds. This restriction was theoretically valid, but was very difficult to apply in practice, and led to incorrect mapping. In the Huntly-Kawhia subdivision, limestones occur at any of five separate stratigraphic horizons. Most of these limestones grade laterally into sandstones, and all are separated in places by thick siltstones. The lowest siltstone, mostly non-calcareous, directly overlies the Coal-measures, and was mapped invariably as "Whaingaroa". The lowest exposed limestone or sandstone was mapped invariably as "Te Kuiti". As a result, the next overlying thick siltstone, the true correlative of Hutton's Whaingaroa Clay, was mapped as "Whaingaroa" only where it was exposed alone (e.g., near Whangape Lake), and as "Te Kuiti" wherever a

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*Gage stated (p. 127B): "The upper portion [of the mudstone] takes on a slightly fissile character, shows faunal affinities with both Hutchinsonian and Waitakian stages, and could be a facies variant of either." Recent sampling of the highest beds (N 92/f507) has yielded only Waitakian faunas. (Mr N. de B. Hornibrook, pers. comm.)

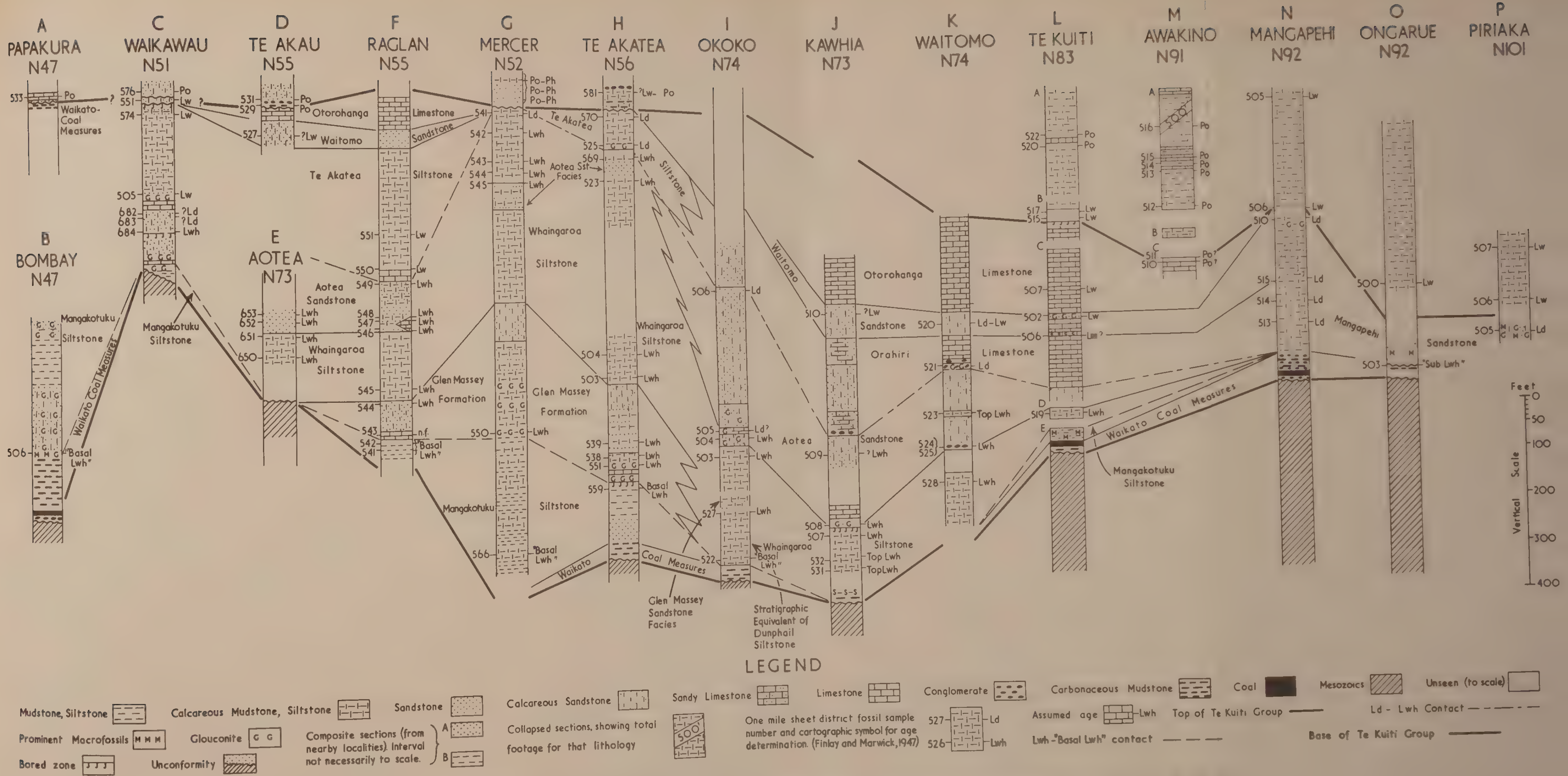

FIG. 2.—Stratigraphic columns; see Fig. 1 and Table 1 for locality and other details. (Foraminiferal age determinations by Mr N. de B. Hornibrook are given in cartographic symbols.)

sandstone or limestone was present below it. This no doubt led to the curious situation whereby Henderson and Grange named their Whaingaroa Beds after Hutton's Whaingaroa Clay, but mapped the type locality of the latter formation as Te Kuiti Beds.

It is considered that the Te Kuiti and Whaingaroa beds are best regarded as a single unit; and that, if subdivision on a group basis were attempted, the undoubted lateral variations would cause serious difficulties, especially from the point of view of subsequent interpretation by other geologists. It is therefore proposed to revert to the original usage of "Te Kuiti", and to fix its base at the bottom of the lowest Tertiary formation.

UPPER LIMIT OF GROUP

In Henderson and Ongley's original definition, the uppermost formation of the Te Kuiti Series was (1923, p. 26) the "blue claystone, everywhere calcareous and in places also arenaceous". These authors, however, also introduced (pp. 28–31) the Mahoenui Series, which immediately overlay the Te Kuiti, and which was stated (p. 28) to consist of "argillaceous beds, in places at least 600 ft thick, which overlie the claystones that form the upper part of the Te Kuiti Series".

In Black Creek basin only did they describe (p. 29) the relationship of the "upper Te Kuiti claystone" to their overlying Mahoenui Series. The latter was reported to consist of two limestones separated by 550 ft of claystone. The upper limestone was shown to overlap westwards on to a limestone of the Te Kuiti Series, and the lower limestone rested upon a "gently undulating surface of argillaceous sandstone" and contained "occasional small fragments of rock similar to" the Te Kuiti beds below. They thus referred the argillaceous sandstone to the Te Kuiti Series and interpreted the contact as unconformable.

Eastwards, the lower Mahoenui limestone was reported to grade into an argillaceous calcareous sandstone which (p. 29) "grades upwards and downwards into claystone with every appearance of conformity. Thus, west of Black Creek, there is overlap and angular unconformity between the Mahoenui and Te Kuiti Series, whereas east of Black Creek deposition appears to have continued uninterruptedly, although with a temporary but decided change in conditions."

The Mahoenui lower limestone at Black Creek (Fig. 2, N) consists of several impure limestone beds, as shown by the following section:

	Ft
(a) Henderson and Ongley's Mahoenui upper limestone	15
(b) Massive calcareous light blue-grey siltstone	500
(c) Massive calcareous siltstones containing sandy limestone beds from 1 to 2 ft thick, lensing out horizontally; small slumping features present and possible large-scale current bedding	15
(d) Limestone, identical to those in (c), with some greywacke pebbles	5
Irregular Surface	
(e) Massive calcareous siltstone, shelly at base, with limestone, 8 ft from top, identical to those in (c)	100

The most prominent limestone (d), which contains greywacke pebbles, has certainly an irregular surface at its base. However,, since a further limestone exists below, and since both this and the enclosing calcareous siltstone are lithologically identical to their counterparts above the irregular surface, the break can have only minor significance, being probably due to contemporaneous erosion. Such an interpretation is in accord with carefully recorded gradational contact to the east, and hence it is preferred to place all the Black Creek basin strata within the same "series".

Little importance is attached to the presence of the greywacke pebbles in the limestone bed ((c) above) as far as delineating the Te Kuiti-Mahoenui contact is concerned. Similar greywacke pebbles represent the chief impurity in flaggy crystalline Te Kuiti limestone, composed very largely of oyster shells, on the road 4 miles due north of Trig. Te Oreure, Otanake S.D.

The massive calcareous siltstones at Black Creek (beds b and e) are typical of those that are widespread in the King Country. Having mapped them at Black Creek as both Te Kuiti and Mahoenui, Henderson and Ongley mapped them within one or the other series elsewhere (e.g., as Te Kuiti at Aria, Piopio, and Troopers Road, and as Mahoenui near Trig. Hangatiki, Orahiri S.D., and along a long stretch of the Great South Road, a few miles south of Te Kuiti). Subsequent authors, continued to refer this massive siltstone, with its rare impure limestone beds, to one or the other "series". Gage (1942) referred it to the Te Kuiti, and Williamson (1932) and Marwick (1946) placed it mainly within the Mahoenui.

It is proposed here to follow the 1928–32 fieldwork, and hence place all the Black Creek strata within the Mahoenui Group. The reported overlapping westwards of the Mahoenui upper limestone on to Te Kuiti limestone is considered a result of pre-Mahoenui deformational movements. Elsewhere, these groups are known to be unconformable, as at Te Akau (Fig. 2, D) and Maramarua Coalfield. Nearer to Te Kuiti, there is a bored zone at Troopers Road (Fig. 2, L), although along the old Mahoenui-Awakino road $\frac{3}{4}$ mile east of Black Creek, only a smooth sharp contact is exposed (Fig. 2, N).

Definition

It is proposed that the basal formation of the Te Kuiti Group be defined as the oldest Tertiary formation at present known in the area west of the Main Divide of the North Island, and south of Auckland city; and the uppermost formation as the topmost flaggy crystalline limestone (Otorohanga Limestone) in the Waitomo Valley (9 miles north of Te Kuiti township) or any equivalent offshore horizon. The upper limit of the group coincides in general with a stratigraphical break, usually erosional, which is generally followed by a coarser and much less calcareous facies.

The oldest formation will be coal measures (as in the original definition of "Te Kuiti Series") which rest invariably with strong unconformity upon Mesozoic rocks. The youngest formation of the group is a limestone, thus completing the traditional transgressional sequence, although many fluctuations are recorded in the marine beds between the basal coal measures and the topmost limestone.

FORMATIONS OF THE TE KUITI GROUP

INTRODUCTION

Every rock unit that is styled a "group" should comprise a number of specified formations. In the case of the Te Kuiti Group, some constituent formations have already been described and named, and new names are now proposed for the rest. All the formations are described and their type localities are specified below. Only the more salient points regarding their distribution are given in the text, however; additional detail may be inferred from Fig. 2. Their sequence and distribution are summarized diagrammatically in Table 2.

Where a name already exists for a formation, reference to its first published use is made in parentheses—e.g., WHAINGAROA SILTSTONE (Hutton, 1867). It is suggested that this form of reference, though brief, would be a most precise way of referring to the definition of any stratigraphical unit. Later amendments to the original could be indicated by using the word "after": "TE KUITI SERIES (Marwick, 1946, after Henderson and Ongley, 1923)", for example, would imply that the beds being described were correlated with Marwick's interpretations of Henderson and Ongley's Te Kuiti Series—i.e., the original Te Kuiti Series, less the Whaingaroa Series and the "upper Te Kuiti Claystone".

WAIKATO COAL MEASURES (HUTTON, 1871)
Coal Measures: 25 to 1,000 ft

TYPE LOCALITY (here designated): Kupakupa Mine, near Huntly, slightly more than a mile upstream from the site of the present railway bridge over the Waikato River, on the western side of the lower Taupiri Gorge (grid reference N 56/662724). The mine entrance was some 150 ft above the river.

TYPE DESCRIPTION: Hutton (1871) gave the following detailed section at Kupakupa Mine, which must be taken as the type:

Yellow sandy clay with nodules of clay ironstone	230 ft plus
Upper fireclay, dark blue	12 to 14 ft
Shale, with leaves of dicotyledons	4 ft
Brown coal	12 to 18 ft
Lower fireclay, light blue	20 ft
Light coloured clay, with ironstone	30 to 100 ft

TABLE 2.—Formations of the Te Kuiti Group showing ages (based mainly upon foraminiferal determinations of Mr N. de B. Hornibrook), and typical lithologies (in terms of three extremely broad regions).

AGE	NORTH AND EAST	CENTRAL	SOUTH AND WEST
Waitakian	OTOROHANGA LIMESTONE Limestone	Limestone	Limestone
Waitakian	WAITOMO SANDSTONE Sandstone	Sandstone	Sandstone
Duntroonian-Waitakian	TE AKATEA SILTSTONE ⟷ ORAHIRI LIMESTONE* Siltstone (locally basal limestone)	Sandstone	Limestone
Whaingaroan-Duntroonian	AOTEA SANDSTONE* (with Waitetuna Limestone Member) Sandstone and Siltstone	Sandstone	Sandstone
Whaingaroan	Siltstone WHAINGAROA SILTSTONE Siltstone	Siltstone	Siltstone
	Siltstone	GLEN MASSEY FORMATION† Sandstone†, Siltstone† and Limestone†	MEASURES thin measures
"Basal Whaingaroan"	MANGAKOTUKU SILTSTONE Siltstone	Siltstone	very coal
Whaingaroan-Arnold	WAIKATO Carbonaceous siltstone and coal	COAL Carbonaceous siltstone and coal	BASEMENT
	HOKONUI	BASEMENT	

* Also may be in part correlatives of the Mangapehi Sandstone (Duntroonian)

† Comprises Glen Massey Sandstone, Dunphail Siltstone, and Elgood Limestone members

DISTRIBUTION AND CONTENT: "Waikato Coal Measures" may be applied usefully to all basal Tertiary coal measures of the North Island, south of Auckland city. Sub-bituminous coal seams, ranging up to nearly 100 ft in thickness, have been mined in the Drury, Maramarua, Huntly, Rotowaro, Glen Massey, Whatawhata, Kawhia, Otorohanga, and Mangapehi coalfields, to which the overall name of Waikato Coal

Region can be conveniently applied. The lowest seam is commonly separated from leached Mesozoic rocks by about 25 ft of fireclays, carbonaceous mudstones, and rarer sandstones and conglomerates.

Except at Mangapehi, where conglomerates are common, the overlying measures are interbedded brown-grey mudstones or siltstones (close to fireclays) and finely bedded more carbonaceous horizons that may pass laterally into coal seams. These upper measures commonly contain lensing beds of siderite concretions. Their total thickness usually varies between 100 ft and 300 ft, but reaches 1,000 ft in parts of Rotowaro Coalfield, and is virtually nothing in the Drury, Kawhia, and Otorohanga fields.

KNOWN AGE RANGE: Lower Arnold (Dr R. A. Couper, pers. comm.) to Whaingaroan (as at Mangapehi).

SYNONYMY: "Brown Coal Formation" (Hochstetter, 1859), "Drury Coal Series" (Hutton, 1871), and "Coal-measures" (Cox, 1877a, 1887b; Henderson and Grange, 1926; Penseler, 1930; and Battey, 1949) are synonyms that are less desirable than "Waikato Coal Measures", the first and third because of the lack of a geographical name, and the second, which was introduced together with "Waikato", because only one name was required. The name of the more important coalfield is now adopted. Other rock units, of which the Waikato Coal Measures of the present paper were a part, are: Papakura Series (Laws, 1931), Whaingaroa Series (Marwick, 1946), and Te Kuiti Series (Henderson and Ongley, 1923; Williamson, 1932; Gage, 1942; and Fyfe, 1945).

MANGAKOTUKU SILTSTONE (NEW FORMATION)

Siltstone, often non-calcareous . . . 100 to 300 ft

NAME DERIVATION: Mangakotukutuku Stream (the final "tuku" is omitted from the formational name for convenience) flows south-eastwards and then northwards from Dunphail Bluffs (2 miles north of Glen Massey) to Rotowaro, where it joins Awaroa Stream.

TYPE LOCALITY AND DESCRIPTION: Dunphail Bluffs—Figs 3 and 4 include details of locality and stratigraphy.

DISTRIBUTION AND CONTENT: Except for the area south of Te Kuiti (e.g., Mangapehi Coalfield), the Waikato Coal Measures are everywhere conformably overlain by Mangakotuku Siltstone, which overlaps them westwards and rest directly upon Mesozoic rocks. For the most part, the formation consists of non-calcareous siltstone, which may exceed 300 ft in thickness. Locally, fossil casts are common, and such calcareous beds as do occur are generally rich in molluscs and corals. A glauconitic sandstone in the middle of the formation at Huntly (within Henderson and Grange's, 1926, p. 46, Whaingaroa Beds), becomes basal southwards and contains thin coal seams near Whatawhata.

KNOWN AGE RANGE: Whaingaroan, possibly Runangan or even Duntroonian locally.

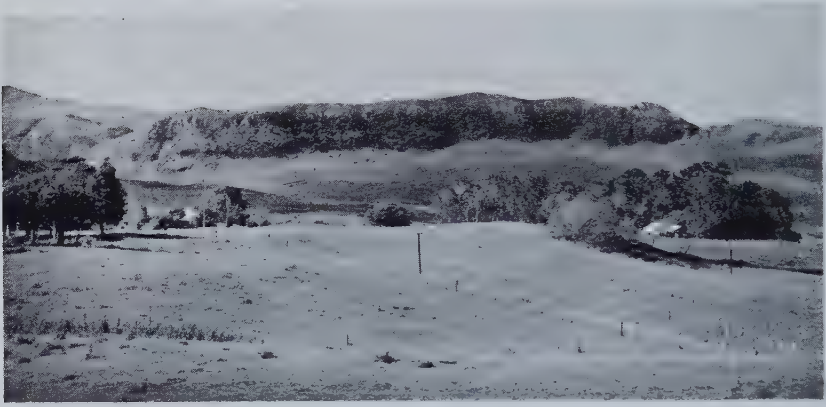

FIG. 3.—(a) Dunphail Bluffs from the south, at the end of Elgood Road, with Mangokotukutuku Stream flowing east below them.

—*G. C. Shaw, photo.*

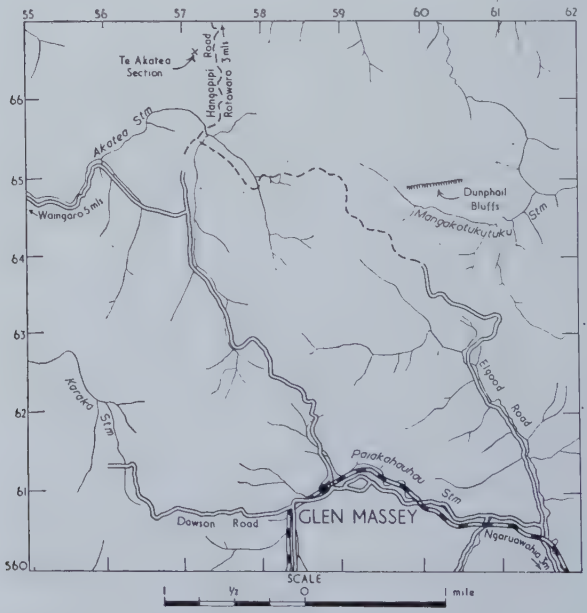

Fig. 3 (b).
Locality map, which also shows the Te Akatea Section.

SYNONYMY: Foraminiferal shale (Bartrum and Branch, 1936, pp. 388, 401); Whaingaroa Formation (Purser, 1952; Dow, 1956); "*Lingula*" Claystone, together with overlying greensand and grey claystone (Penseler, 1930, pp. 134–6); and lower part of Whaingaroa "Beds" or "Series" (Henderson and Grange, 1926; Marwick, 1946).

GLEN MASSEY FORMATION (NEW FORMATION)

Calcareous sandstone, with basal siltstone and limestone members . . . 100 to 200 ft

NAME DERIVATION: Glen Massey village (Fig. 3), 5 miles west of Ngaruawahia.

TYPE LOCALITY AND DESCRIPTION: Dunphail Bluffs—Figs 3 and 4 include details of locality, of stratigraphy, and of the three constituent members: a near-basal limestone (Elgood), an intermediate siltstone (Dunphail), and an uppermost prominent sandstone (Glen Massey).

ELGOOD LIMESTONE MEMBER: Elgood Road (Fig. 3) extends northwards from the Ngaruawahia-Glen Massey Road, 2 miles east of the latter village. At the Dunphail Bluffs type section, the Elgood Limestone Member is exposed in lenses up to 10 ft thick (Fig. 4). The limestone is present within a basal highly glauconitic sandstone that emphasizes the significant change from the dominantly sheltered, anaerobic facies of the Mangakotuku Siltstone to the open sea facies of the Glen Massey Formation.

DUNPHAIL SILTSTONE MEMBER: Dunphail Bluffs are at the head of Mangakotukutuku Stream (Fig. 3). The calcareous siltstone, 30 ft thick, that overlies the basal glauconitic sandstone there, is named the Dunphail Siltstone Member (Fig. 4).

GLEN MASSEY SANDSTONE MEMBER: The Glen Massey Sandstone Member, which has the upper 120 ft of calcareous sandstone at Dunphail Bluffs as its type locality, is the most conspicuous and widespread unit of the Glen Massey Formation. It forms prominent bluffs of calcareous fine sandstone, from which large blocks have commonly fallen to litter the muddy slopes below.

DISTRIBUTION AND CONTENT: The Glen Massey Formation is exposed in west Auckland province from the Port Waikato area southwards to Karioi and Pirongia mountains. In the Maramarua and Kawhia coalfields, the formation as such is missing, but is probably represented by minor sandy beds within the Whaingaroa Siltstone.

The basal glauconitic sandstone, locally a greensand, is a widely recognizable bed, and is especially obvious in drill cuttings when drillholes are penetrating that horizon. This is true also in the Maramarua Coalfield, where the greensand is the basal bed of the Whaingaroa Siltstone. The Elgood Limestone is lensoid, and is frequently absent, but at Karamu it reaches 100 ft in thickness and has well-known caves developed within it. The Dunphail Siltstone has southerly and westerly limits of distribution at Karamu and Ruawaro respectively. The Glen Massey Sandstone has a wide and prominent distribution throughout west Auckland, where bluffs of its calcareous sandstone average about 75 ft in height, and may exceed 100 ft locally. Many "limestone" analyses are available from the Raglan County area (Morgan, 1919, pp 79–83; Henderson and Grange, 1926, pp. 92–5), and many of those in the range 45 to 65% calcium carbonate would be from the Glen Massey Sandstone.

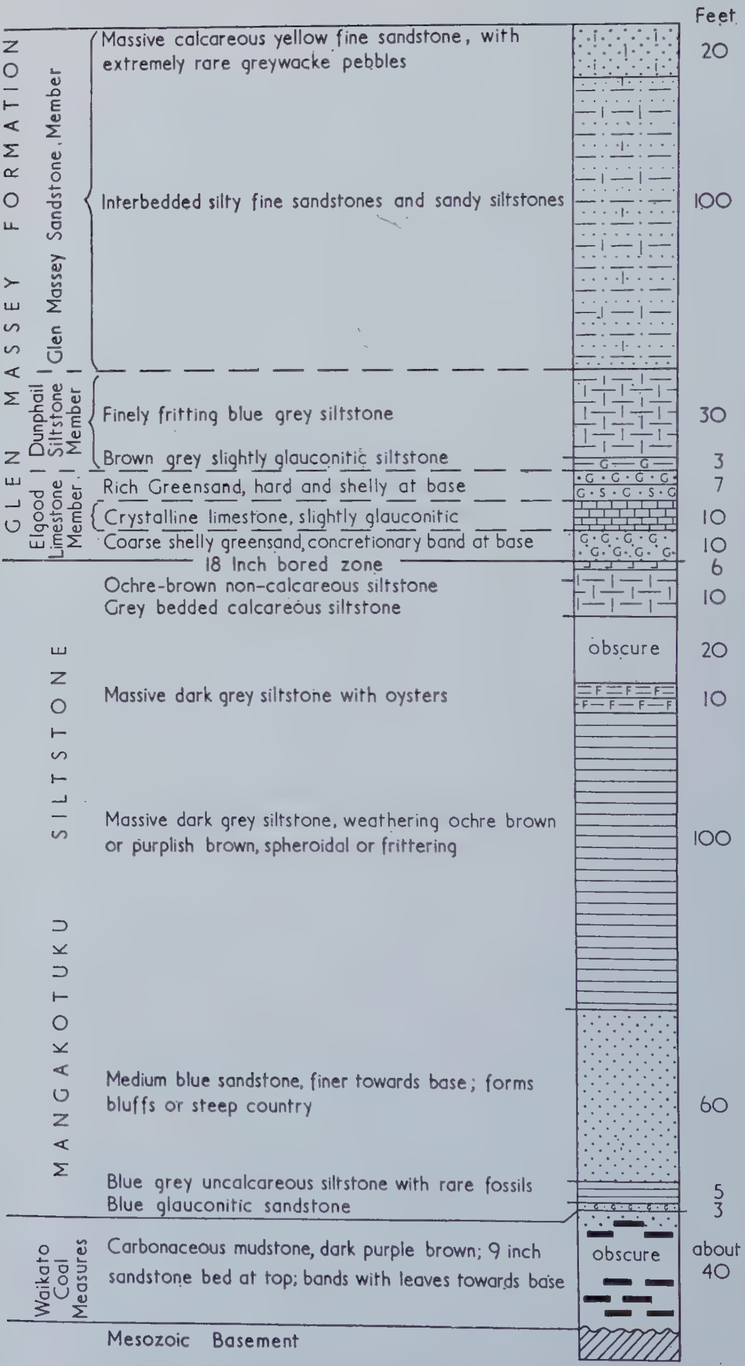
Feet
GLEN MASSEY FORMATION
Glen Massey Sandstone Member
Massive calcareous yellow fine sandstone, with extremely rare greywacke pebbles
20
Interbedded silty fine sandstones and sandy siltstones
100
Dunphail Siltstone Member
Finely fritting blue grey siltstone
30
Brown grey slightly glauconitic siltstone
3
Elgood Limestone Member
Rich Greensand, hard and shelly at base
7
Crystalline limestone, slightly glauconitic
10
Coarse shelly greensand, concretionary band at base
10
18 Inch bored zone
6
MANGAKOTUKU SILTSTONE
Ochre-brown non-calcareous siltstone
Grey bedded calcareous siltstone
10
obscure
20
Massive dark grey siltstone with oysters
10
Massive dark grey siltstone, weathering ochre brown or purplish brown, spheroidal or frittering
100
Medium blue sandstone, finer towards base; forms bluffs or steep country
60
Blue grey uncalcareous siltstone with rare fossils
5
Blue glauconitic sandstone
3
Waikato Coal Measures
Carbonaceous mudstone, dark purple brown; 9 inch sandstone bed at top; bands with leaves towards base
obscure
about 40
Mesozoic Basement

FIG. 4.—Detail of rocks exposed at Dunphail Bluffs (type sections of Mangakotuku Siltstone and of Glen Massey Formation and its members—Elgood Limestone, Dunphail Siltstone, and Glen Massey Sandstone). Locality shown on FIG. 3 (b).

KNOWN AGE RANGE: Whaingaroan.

SYNONYMY: Papakura "Series" and/or Aotea Sandstone (Hutton, 1867; Cox, 1877a, 1877b); Te Kuiti Beds, etc. (Henderson and Grange, 1926, pp. 47–9; Penseler, 1930, p. 136; Battey, 1949, pp. 433–4; Purser, 1952; Dow, 1956; and Kear, 1957).

The "Papakura Limestone" of some early writers on the Waikato area (e.g., Hutton, 1867, p. 5; and Cox, 1877a, p. 13) was presumably the Elgood Limestone—stratigraphically well below the type Papakura Limestone.

WHAINGAROA SILTSTONE (HUTTON, 1867)

Calcareous siltstone . . . 150 to 400 ft

TYPE LOCALITY (here designated): Hochstetter's earlier locality (1864, p. 44)—near Capt. Johnston's house on the shore of Waitetuna Creek—must be taken as the type, because Hutton (1867, p. 6) recorded no more precise locality than Whaingaroa [Raglan] Harbour.

TYPE DESCRIPTION: A cliff section exposing 150 ft of medium blue-grey calcareous siltstone.

DISTRIBUTION AND CONTENT: The formation is exposed from Tuakau (Battey, 1949, p. 434) southwards to Te Kuiti. Everywhere it is a medium blue-grey calcareous siltstone with a characteristic conchoidal fracture. Bedding is generally absent, but thin sandstone beds are present locally, especially towards the upper gradational contact with the Aotea Sandstone. The lower contact with the Glen Massey Formation is gradational, and usually corresponds to the top of prominent bluffs. In some areas, especially of the Maramarua and Kawhia coalfields, the Whaingaroa Siltstone thickens locally at the expense of the Glen Massey Sandstone.

KNOWN AGE RANGE: Whaingaroan, possibly to Duntroonian.

SYNONYMY: Clay Marls, or Leda Marls, at Waitetuna Estuary (Cox, 1877a, 1877b); Marly Greensands (McKay, 1884, pp. 142–3); Te Kuiti Series (Henderson and Ongley, 1923); Whaingaroa Beds at Whangape Lake, etc., or Te Kuiti Beds at Glen Afton, Glen Massey, Waitetuna Estuary, etc. (Henderson and Grange, 1926); and Whaingaroa Beds (Marwick, 1946).

AOTEA SANDSTONE (HUTTON, 1867)

Calcareous sandstone . . . 50 to 250 ft

TYPE SECTION (here designated): Hochstetter's earlier locality (1864, p. 45)—Orotangi bluffs in south-east Aotea Harbour—must be taken as the type, because Hutton (1867, p. 6) did not visit Aotea.

TYPE DESCRIPTION: Grey calcareous fine-medium sandstone, 50 ft thick (type Aotea Sandstone), overlies 60 ft of calcareous siltstone (Whaingaroa Siltstone), of which the lower 40 ft is massive. The contact is gradational.

WAITETUNA LIMESTONE MEMBER: Around the upper Waitetuna Estuary (Raglan Harbour), to the south of the type Whaingaroa Siltstone section, a light-coloured flaggy crystalline limestone is exposed above what appears to be a genuine correlative of the Whaingaroa Siltstone. Local stratigraphical sequences leave little doubt that this is the local equivalent of the Aotea Sandstone, as, indeed, Hochstetter believed (1864, pp. 44–5). Elsewhere, a limestone appears within the Aotea Sandstone, especially close to the base of the formation, and this is named the Waitetuna Limestone Member. Maunurima Creek, a tributary of Waitetuna River, is nominated as the type locality, with the type section exposed immediately upstream from the road crossing.

DISTRIBUTION AND CONTENT: At Motutara Point (Kawhia Harbour), as at its type locality, the Aotea Sandstone grades up from the Whaingaroa Siltstone, but its top is not exposed. At Hauturu (south-eastern Kawhia Harbour) and in the lower Te Kauri valley, 1½ miles to the north-east, the Whaingaroa Siltstone grades up into glauconitic and sandy beds that are themselves overlain by a prominent flaggy limestone (Waitetuna Limestone Member) either gradationally or with bored contact. The beds above the limestone are unexposed, but the formation is eventually completed (at Hautapu Hill) by a calcareous sandstone.

Calcareous sandstones, correlated with the Aotea Sandstone, are stratigraphically higher than correlatives of the Whaingaroa Siltstone at Waitomo (Fig. 8), although the contact is not exposed. They are overlain directly by the type Orahiri Limestone which is a lateral equivalent of the Te Akatea Siltstone. At the type locality of the latter formation an Aotea Sandstone facies occurs within thick Whaingaroa Siltstone (Fig. 5).

To the north of Raglan and west of Te Akatea (e.g., at Te Akau and Waikawau), the Aotea Sandstone is represented by interbedded calcareous siltstones and glauconitic sandstones (commonly with a thin basal massive sandstone), up to 75 ft thick, and/or by the Waitetuna Limestone Member. In a drillhole at Mercer, a calcareous sandstone horizon, 450 ft above the Mangakotuku Siltstone, probably represents the Aotea Sandstone within thick Whaingaroa Siltstone.

Thus the base of the Aotea Sandstone is characterized by a change to sandstone or limestone facies from that of a siltstone. Locally in the north (e.g., at Te Akatea and Mercer), siltstones are present above the Aotea Sandstone and the latter is considered as a minor facies within the Whaingaroa Siltstone. To the south, the distinction of the upper Aotea Sandstone from the sandy beds of the Orahiri Limestone is not easy, unless the pebbly contact is exposed.

KNOWN AGE RANGE: Whaingaroan (predominantly) to Duntroonian.

SYNONYMY AND CORRELATION: Whilst retaining Aotea Sandstone, Hutton (1871) introduced "Aotea Series", of a group rank, as embracing

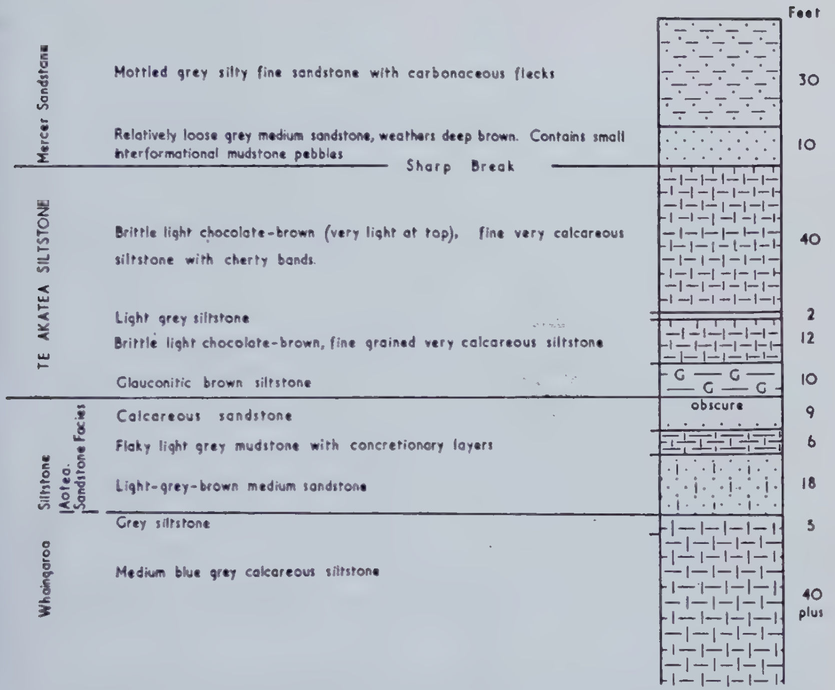
Feet
Mercer Sandstone
Mottled grey silty fine sandstone with carbonaceous flecks
30
Relatively loose grey medium sandstone, weathers deep brown. Contains small interformational mudstone pebbles
10
Sharp Break
TE AKATEA SILTSTONE
Brittle light chocolate-brown (very light at top), fine very calcareous siltstone with cherty bands.
40
Light grey siltstone
2
Brittle light chocolate-brown, fine grained very calcareous siltstone
12
Glauconitic brown siltstone
G
10
obscure
Aotea. Sandstone Facies
Calcareous sandstone
9
Flaky light grey mudstone with concretionary layers
6
Light-grey-brown medium sandstone
18
Whaingaroa Siltstone
Grey siltstone
5
Medium blue grey calcareous siltstone
40 plus

Fig. 5.—Detail of rocks exposed at Te Akatea (type section of Te Akatea Siltstone). Locality shown on Fig. 3 (b).

most of the marine rocks of the present Te Kuiti Group. His assumption that the "Papakura Series" underlay the Aotea was erroneous, if the former be interpreted as a true correlative of the Papakura Limestone. Thus, Cox's later usage (1877a, 1877b) of restricting "Aotea" to the sandstone formation is preferable. Cox, like Hutton, could not visit Aotea and the King Country, and was forced to map many sandstones as "Aotea" that he might otherwise have separated (e.g., those at Te Hara Point, near Te Akau, that are now mapped as Waitomo Sandstone).

Henderson and Grange (1926) re-mapped most of the earlier authors' Aotea Sandstone as Te Kuiti Beds, and Marwick (1946) would have mapped them as either Te Kuiti or Whaingaroa Series. Purser (1952) and Dow (1956), in re-mapping the north-western part of the Huntly-Kawhia Subdivision, placed the Waitetuna Limestone Member at the top of the Te Kuiti Formation.

Te Akatea Siltstone (New Formation)

Very calcareous siltstone . . . 60 to 250 ft

Name Derivation: Te Akatea Stream, a tributary to Waingaro Stream, flows generally westwards from the hills between Glen Massey and Glen Afton villages.

TYPE LOCALITY AND DESCRIPTION: Te Akatea Section—Figs 3 and 5 include details of locality and stratigraphy. The Te Akatea Siltstone is overlain, unconformably, by sandstones that are correlated with the Mercer Sandstone of Cox (1877b, pp. 13, 22–3), and that would be included within the Waikawau Group (Kear, 1957, p. 834).

DISTRIBUTION AND CONTENT: Near Te Kotuku Trig. Station on the northern side of Raglan Harbour (Fig. 1), the Te Akatea Siltstone comprises about 200 ft of calcareous siltstone, with prominent fine sandstone members and a basal white sandy limestone (the "Raglan Limestone" of some authors). Farther north, near Waikawau Stream mouth, these massive, light-coloured, very calcareous siltstones underlie type Waikawau Beds (Henderson and Grange, 1926, p. 55).

Around Kawhia Harbour, and southwards from there into the King country, the formation that occupies the same stratigraphic position as the Te Akatea Siltstone ranges from a crystalline limestone to a very calcareous sandstone. It has been mapped separately as the Orahiri Limestone (see below). Thus, the Te Akatea Siltstone occupies only the northern part of the area covered by the Te Kuiti Group.

KNOWN AGE RANGE: Duntroonian to Waitakian.

SYNONYMY: Aotea Series, in part (Hutton, 1871); Te Kuiti Beds, at Te Akau (Henderson and Grange, 1926); Mahoenui Beds at Waikawau (Henderson and Grange, 1926; Purser, 1952; Dow, 1956); Te Kuiti Group at Kaawa-Ohuka (Kear, 1957); and lateral equivalent of Orahiri Limestone (present paper).

ORAHIRI LIMESTONE (NEW FORMATION)

Crystalline limestone . . . 50 to 100 ft

NAME DERIVATION: Orahiri Survey District.

TYPE LOCALITY AND DESCRIPTION: Worths Quarry in Orahiri Survey District—Figs 6 and 7 include details of locality and stratigraphy.

DISTRIBUTION AND CONTENT: At Te Kuiti (e.g., at Beros' Quarry south of the township), beds that have been collectively called the "Te Kuiti Limestone" comprise an upper and a lower limestone that are separated by a glauconitic very calcareous sandstone (Fig. 2, L). The lower limestone is correlated with the Orahiri Limestone. The Orahiri Limestone is represented at Hautapu Hill, Kawhia Harbour, by calcareous sandstones and sandy limestones of the central part of the bluffs (Fig. 2, J); and west of the Okoko Valley (Okoko Section, Fig. 2, I) by the exposures of calcareous sandstone in the upper of the road cuttings of the long hill east of Te Rauamoa.

KNOWN AGE RANGE: Duntroonian, possibly to Waitakian.

SYNONYMY: Te Kuiti Limestone, lower part (many authors—e.g., Marwick, 1946, p. 11); Te Kuiti "Series" or "Beds" (Henderson and Ongley, 1923; Henderson and Grange, 1926; Marwick, 1946); and

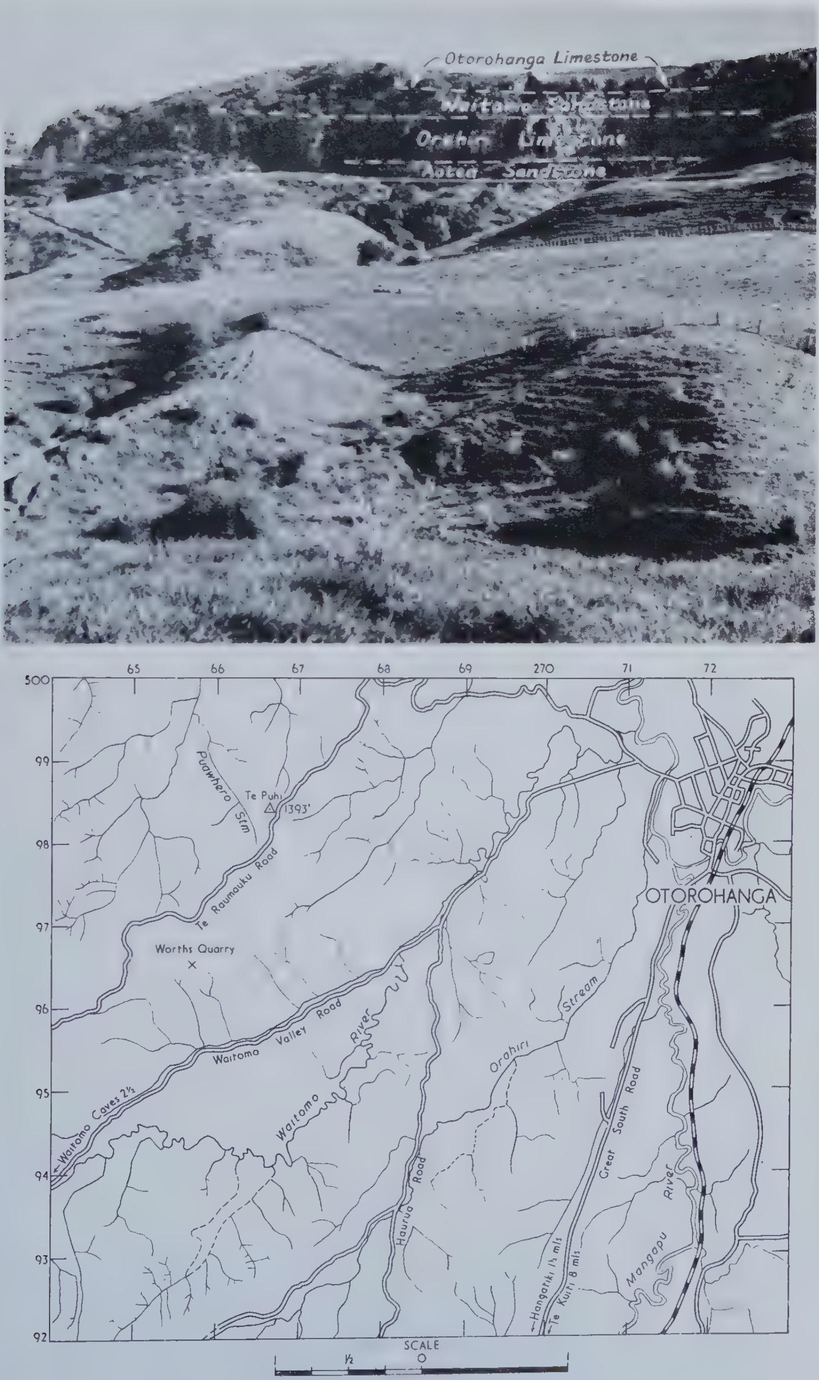

FIG. 6.—(a) Worths Quarry from east; (b) locality map.

lateral equivalent of Te Akatea Siltstone and possibly Mangapehi Sandstone (present paper).

WAITOMO SANDSTONE (NEW FORMATION)

Calcareous glauconitic sandstone . . . 30 to 50 ft

NAME DERIVATION: Waitomo Valley Road, 4 miles west-south-west of Otorohanga.

TYPE LOCALITY AND DESCRIPTION: Worths Quarry—Figs 6 and 7 include details of locality and stratigraphy.

DISTRIBUTION AND CONTENT: At Beros' eastern limestone quarry, and elsewhere near Te Kuiti, the Waitomo Sandstone is represented by 50 ft of glauconitic calcareous sandstone. At the western quarry, the upper 40 ft of this formation has graded laterally into a glauconitic impure sandy limestone. At Hautapu Hill, Kawhia, 65 ft of calcareous glauconitic sandstone that underlies the topmost flaggy limestone, is correlated with the Waitomo Sandstone. To the north of Raglan Harbour, the formation is represented by a fossiliferous calcareous medium sandstone that is much coarser and much more fossiliferous than any sandstone member of the underlying Te Akatea Siltstone. It was mapped by Cox (1877b, p. 25) as Aotea Sandstone at Te Hara Point, near to which it was figured by Henderson and Grange (1926, Plate II, Fig. 4); and it is also well exposed above Te Akatea Siltstone at the northern end of Carters Beach.

KNOWN AGE RANGE: Waitakian, possibly Duntroonian.

SYNONYMY: Aotea Sandstone, at Te Hara Point (Cox, 1877a, 1877b); Te Kuiti "Beds", "Series", or "Limestone" (many authors). The "*Cardita*" Beds (Cox, 1877b, pp. 15–6) are separated by bored surfaces from the underlying Te Akatea Siltstone and from the overlying Waikawau Stream mouth. Further fieldwork is required to ascertain true relationships, but the "*Cardita*" Beds might be correlatives of the Waitomo Sandstone.

OTOROHANGA LIMESTONE (NEW FORMATION)

Crystalline limestone . . . 50 to 200 ft

NAME DERIVATION: Otorohanga Borough.

TYPE LOCALITY AND DESCRIPTION: Worths Quarry—Figs 6 and 7 include details of locality and stratigraphy.

DISTRIBUTION AND CONTENT: The Otorohanga Limestone is the highest limestone of the Te Kuiti Group and is widely distributed throughout the King Country, in many places immediately beneath the mudstones or limestones of the Mahoenui Group. At the Otorohanga Limestone Co.'s quarry, 1¾ miles south-west of the type locality, it is 200 ft thick.

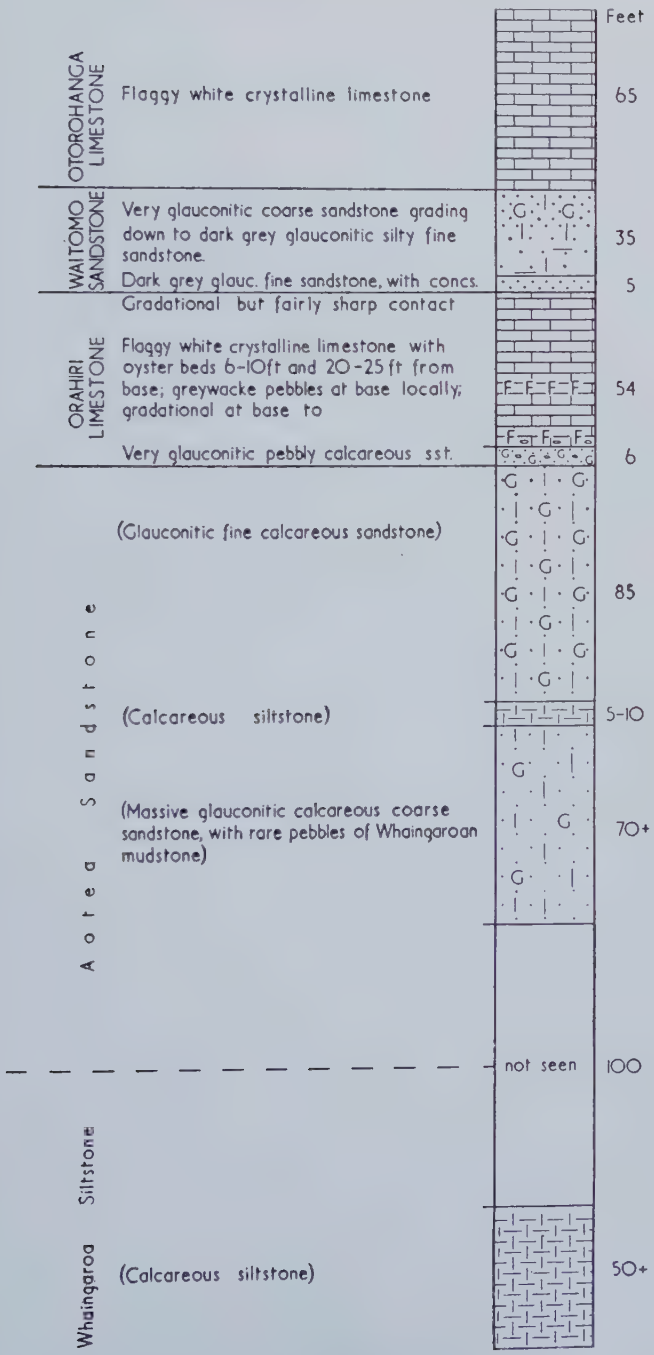
Feet
OTOROHANGA LIMESTONE
Flaggy white crystalline limestone
65
WAITOMO SANDSTONE
Very glauconitic coarse sandstone grading down to dark grey glauconitic silty fine sandstone.
35
Dark grey glauc. fine sandstone, with concs.
5
Gradational but fairly sharp contact
ORAHIRI LIMESTONE
Flaggy white crystalline limestone with oyster beds 6-10ft and 20-25ft from base; greywacke pebbles at base locally; gradational at base to
54
Very glauconitic pebbly calcareous sst.
6
Aotea Sandstone
(Glauconitic fine calcareous sandstone)
85
(Calcareous siltstone)
5-10
(Massive glauconitic calcareous coarse sandstone, with rare pebbles of Whaingaroan mudstone)
70+
not seen
100
Whaingaroa Siltstone
(Calcareous siltstone)
50+

FIG. 7.—Detail of rocks exposed at Worths Quarry (type sections of Orahiri Limestone, Waitomo Sandstone, and Otorohanga Limestone). [Beds shown in brackets are exposed across a fault to the south-west of the type sections.] Locality shown on Fig. 6 (b).

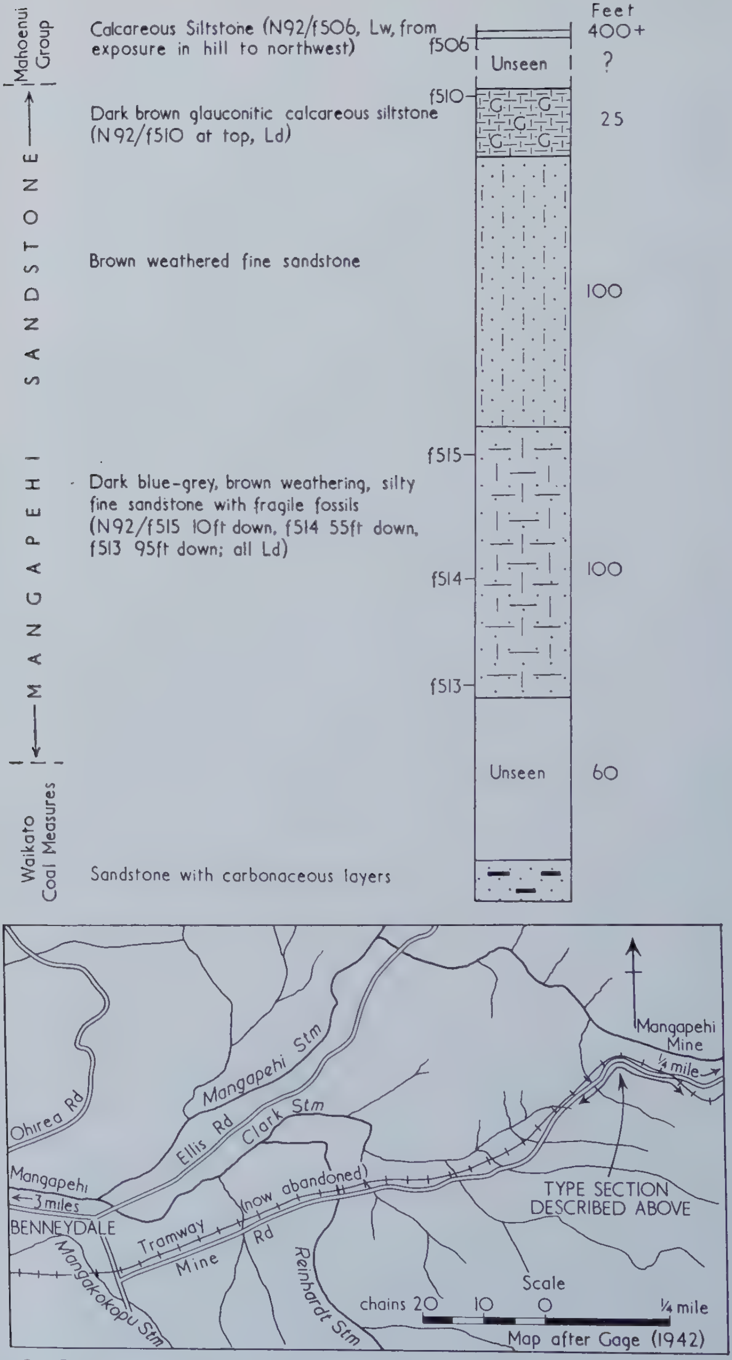
Mahoenui Group
Calcareous Siltstone (N92/f506, Lw, from exposure in hill to northwest)
Feet
400+
f506
Unseen
?
f510
Dark brown glauconitic calcareous siltstone (N92/f510 at top, Ld)
G
25
MANGAPEHI SANDSTONE
Brown weathered fine sandstone
100
f515
Dark blue-grey, brown weathering, silty fine sandstone with fragile fossils (N92/f515 10ft down, f514 55ft down, f513 95ft down; all Ld)
f514
100
f513
Unseen
60
Waikato Coal Measures
Sandstone with carbonaceous layers
Ohirea Rd
Mangapehi Stm
Ellis Rd
Clark Stm
Mangapehi
←3 miles
BENNEYDALE
Mangakokopu Stm
Tramway (now abandoned)
Mine Rd
Reinhardt Stm
Mangapehi Mine
¼ mile→
TYPE SECTION DESCRIBED ABOVE
Scale
chains 20 10 0 ¼ mile
Map after Gage (1942)

Fig. 8.—Detail of rocks exposed in cuttings at Benneydale (type section of Mangapehi Sandstone), with locality map.

At Te Kuiti itself, it forms the upper 140 ft of limestone in Beros' and other limestone quarries (Fig. 2, B).

At Hautapu Hill, Kawhia, it comprises 100 ft of crystalline limestone, in which large oysters are common, and on the coast south of Te Akau (south of Fig. 2, D; also Henderson and Grange, 1926, Plate II, Fig. 3), it comprises up to 70 ft of flaggy crystalline fossiliferous limestone containing large oysters, pectens, and numerous brachipods. It is there overlain unconformably by younger conglomerates.

KNOWN AGE RANGE: Waitakian, possibly to Otaian at Awakino Valley tunnel (Fig. 2, M).

SYNONYMY: Kawhia Limestone in part or in full (Cox 1877b, p. 25; and other authors); upper part of Te Kuiti "Series", "Beds", or "Limestone" (Henderson and Ongley, 1923; Henderson and Grange, 1926; Marwick, 1946).

MANGAPEHI SANDSTONE (NEW FORMATION)

NAME DERIVATION: Mangapehi Settlement (Figs 1, 8).

TYPE LOCALITY AND DESCRIPTION: Mangapehi Mine Section—Fig. 8 includes details of locality and stratigraphy. The mine works a coal seam in the Waikato Coal Measures.

DISTRIBUTION, CONTENT, AND CORRELATION: Gage (1942, pp. 126B–127B) stated that the upper part of his lower Te Kuiti Series comprised Duntroonian marine sandstones (the Mangapehi Sandstone of this paper). Similar sandstones have been recorded from the upper Wanganui by Fyfe (1945), and are present in the banks of the Wanganui River at Piriaka (Fig. 2, P). Fyfe recorded two sandstones from the area of Hemopo Creek (1945, p. 208), of which the lower (300 ft of Duntroonian calcareous sandstone) at least would be a correlative of the Mangapehi Sandstone. The upper sandstone (720 ft of calcareous sandstone with basal conglomerate) is a probable correlative of sandstones at Ongarue, but there is still doubt as to whether these two should be placed within the Te Kuiti Group, or should be considered as basal Mahoenui (Kear, 1952, pp. 61–3).

There is no certain correlation between the Mangapehi Sandstone and the other formations of the Te Kuiti Group. Possibly a lateral change of facies of the Orahiri Limestone occurs between Te Kuiti and Mangapehi that is similar to the known change between Waitomo and Kawhia. At Hautapu Hill (Kawhia), the limestone formation has graded into a calcareous sandstone with limestone beds. In the upper Wanganui, Fyfe (1945, p. 208) inferred that blocks of limestone were derived from a stratigraphical position closely above the coal, and therefore presumably at the base of the Mangapehi Sandstone. These could be basal Orahiri Limestone; and the overlying sandstone could represent the balance of that formation and possibly the Waitomo Sandstone as well. However, such correlations are extremely tenuous at present, especially since the Mangapehi and Aotea sandstones are possible correlatives.

KNOWN AGE: Duntroonian.

SYNONYMS: Te Kuiti, and Orahiri Limestone (see Distribution, etc., above).

TOP OF THE TE KUITI GROUP

Mr N. de B. Hornibrook (pers. comm.) has identified Otaian Foraminifera from sandstones at Pokeno that overlie Whaingaroa Siltstone, and that contain coal pebbles with a microflora like that of the Waikato Coal Measures (Dr R. A. Couper, pers. comm.). The large implied unconformity is also apparent at Maramarua, where similar sandstones rest directly upon Mangakotuku Siltstone. At Kaawa, an erosional interval separates Waikawau limestone and sandstone from the Te Kuiti Group (Kear, 1957, p. 834), the latter group being locally represented by the Te Akatea Siltstone. At Te Akau (Fig. 2, D), conglomerates and sandstones overlie the Otorohanga Limestone or the Waitomo Sandstone unconformably (Henderson and Grange, 1926, p. 54, Plate II, Figs 3, 4), and these conglomerates and sandstones are correlated with the Waikawau Group (Kear, 1957). At Te Akatea (Fig. 2, H), Waikawau sandstones containing possible Waitakian to Otaian Foraminifera (Mr N. de B. Hornibrook, pers. comm.) overlie the Te Akatea Siltstone unconformably. A mile to the east, they overlie the Whaingaroa Siltstone. At Black Creek, and Awakino generally, the reported westward overlap of Mahoenui limestone and sandstone on to Te Kuiti limestone (Henderson and Ongley, 1923; see above) is readily explicable in terms of a pre-Mahoenui unconformity.

Thus, the top of the Te Kuiti Group is represented by an unconformity in many localities, and usually coincides with a change to a more sandy and less calcareous formation, of the Waikawau Group in the north or of the Mahoenui Group in the south. Indeed, such contacts appear to be the rule rather than the exception. The highest formation of the Te Kuiti Group that is exposed below the unconformity ranges from Otorohanga Limestone to Mangakotuku Siltstone, but the presence of pebbles from Waikato Coal Measures in Otaian sandstones at Pokeno indicates that erosion locally had proceeded at least down to these Coal Measures.

PALEOGEOGRAPHY

By J. C. SCHOFIELD

INTRODUCTION

Distribution of land and sea during deposition of the Te Kuiti Group must have been less regular than the following generalized descriptions of isopachs and facies show. For example, drillhole exploration in the

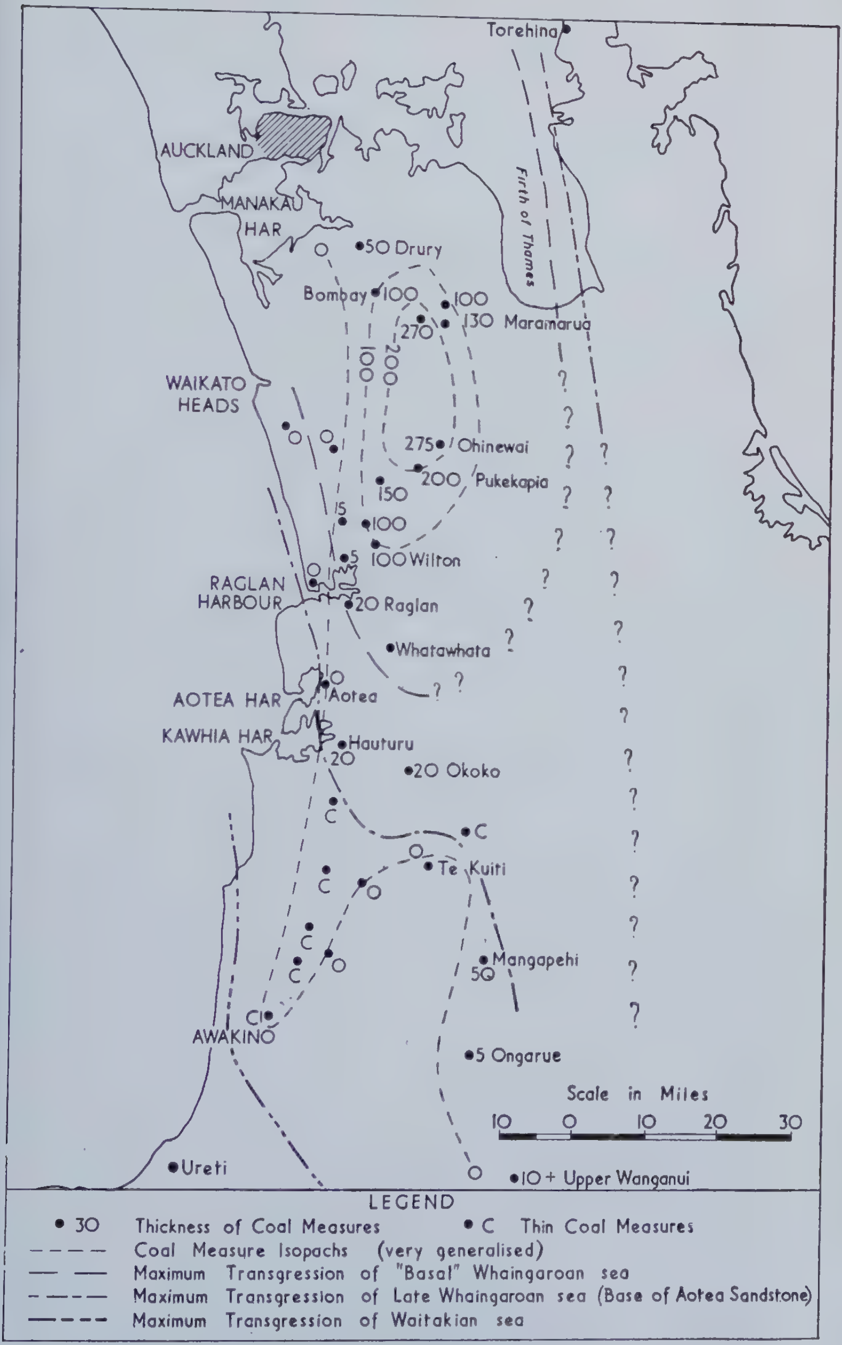

FIG. 9.—Shore-line migration and coal measure isopachs.

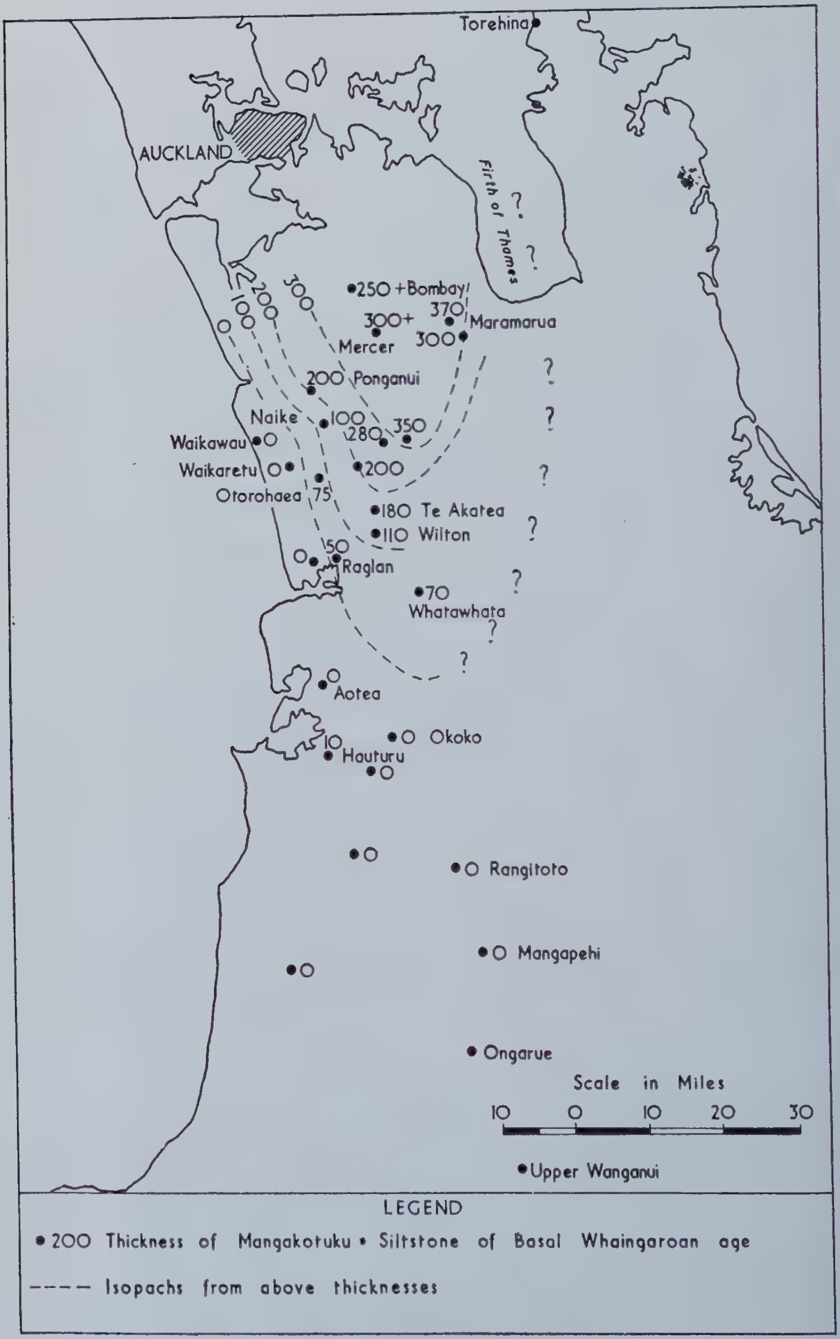

FIG. 10.—Isopachs of Mangakotuku Siltstone.

Rotowaro Coalfield shows that the pre-Coal Measure landscape was cut by deep valleys, and similar valleys might have become inlets during transgression by the sea. Likewise, it is known that the coast line during transgression of the "Basal Whaingaroan" sea was also quite irregular. These minor irregularities cannot be shown on the scale of the accompanying figures. Nor should they be, for outside this portion of the Coalfield, information is so scattered that only very generalized isopachs and facies maps are warranted (Figs 9, 10, 11, 12).

Since preparation of this paper, additional sections of the Awakino area were kindly supplied by Shell B.P. and Todd Oil Services Limited. These confirm the isopach trends of Fig. 11 in that area, but show that the sediments may be slightly thicker at the centre than they are shown to be.

ISOPACHS

In plotting thicknesses to produce the isopachs of Figs 9, 10, and 11, no allowance has been made for erosion that has possibly occurred at three horizons. These are (1) at the top of the Mangakotuku Siltstone, as shown by a bored zone and pebbles at the base of the overlying formation, and a change from anaerobic conditions; (2) at the top of the Whaingaroa Siltstone, as shown by greywacke pebbles and siltstone pebbles of Whaingaroan age at the base of the overlying Aotea Sandstone at Waitomo, and the probable inclusion of a Whaingaroan siltstone boulder in the Aotea Sandstone at Aotea Harbour; and (3) at the top of the Aotea Sandstone, as shown by bored zones and pebbles at the base of the overlying Orahiri Limestone. None of these breaks is perceptibly angular, and uplift of sediments to above sea-level, if any occurred, must have been confined to small areas.

Although no allowance has been made for any possible erosion, the isopachs for the formations of Whaingaroan and Arnold age (Figs 9, 10, and 11) are essentially parallel. Hence, either erosion during the time represented by the above described disconformities has been slight, or differential earth-movements have been relatively constant about the same axis during Arnold and Whaingaroan times. Paralellism does not disprove disconformity or even unconformity.

SHORELINES

Shorelines during the deposition of the Te Kuiti Group (Fig. 9) roughly paralelled isopach trends. As the shoreline migrated south and west, successively younger formations overlapped on to basement or Coal Measures. For example, a westward migration of the shoreline is shown by Dunphail Siltstone on Coal Measures at Okoko, Whaingaroa Siltstone on Coal Measures at Te Kauri (10 miles west of Okoko), and by Aotea Sandstone on basement west of Hautapu (Fig. 1). A similar type of southward transgression can be traced with the aid of Figs 1 and 2.

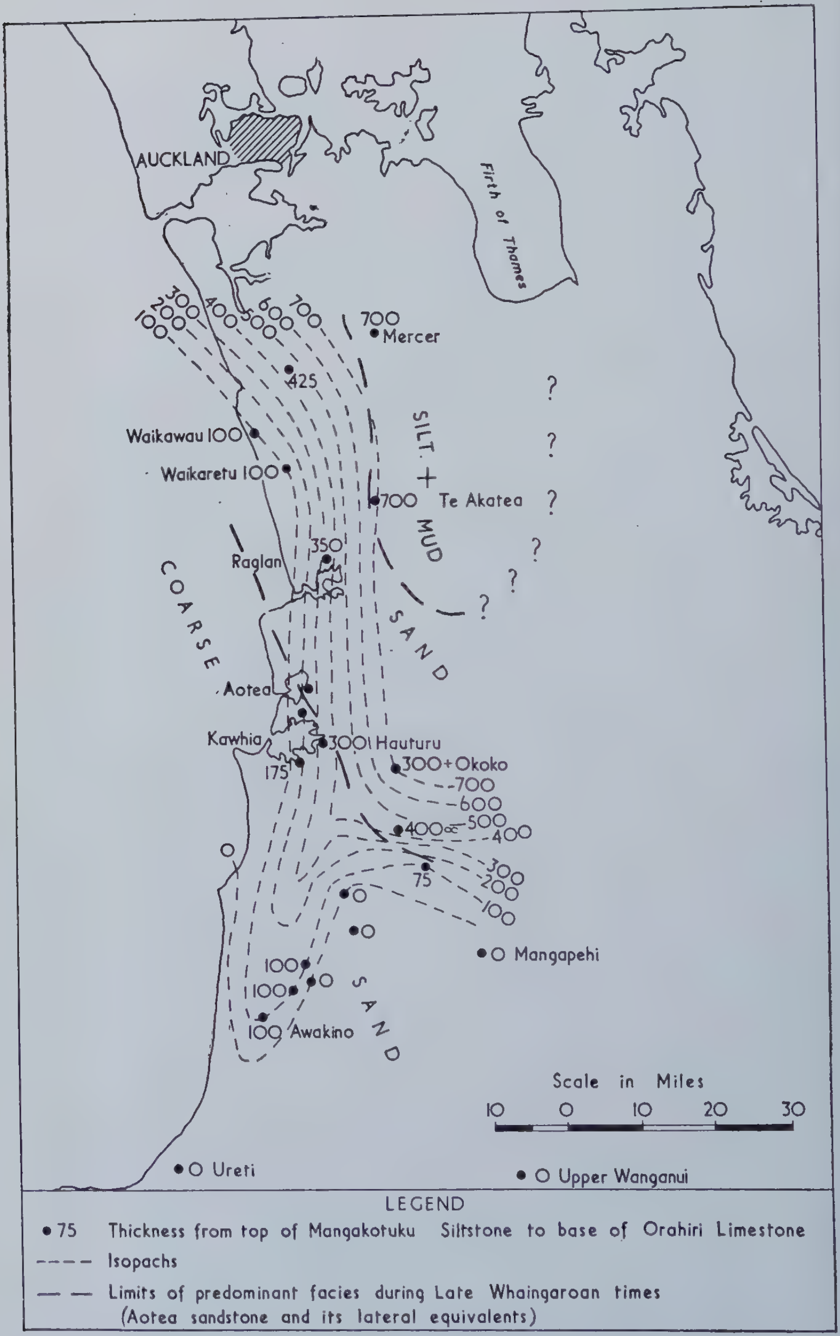

FIG. 11.—Isopachs of sediments of Whaingaroan age (excepting Mangakotuku Siltstone). Facies map of sediments of late Whaingaroan age.

The approximate maximum transgression in the Waitakian is based on the complete absence of the Te Kuiti Group south-west of its mapped position (Fig. 9). Its absence, however, could be due to erosion prior to the deposition of the younger Tertiary formations.

FACIES

Vertical Distribution of Facies

The vertical distribution of facies is that of the usual transgressional sequence of Coal Measures to limestone, and favours the inclusion of all these formations in a single group. The general upward change in facies (Fig. 2) is shown by four horizons. These consist of (1) Coal Measures at the base, (2) interbedded non-calcareous and calcareous siltstones and sandstones deposited in land-locked seas, (3) interbedded open-sea, calcareous sandstones, siltstones, and minor limestones, and finally (4) the widespread Otorohanga Limestone. The latter probably extended south through the Upper Wanganui area (Grange, 1930; Fyfe, 1945) to at least as far as National Park (Mr D. R. Gregg pers. comm.). It is not known if it extended over Te Akatea or Mangapehi, but it is more persistent than the lower limestones.

Lateral Distribution of Facies

Figures 11 and 12 show the lateral distribution of facies whilst the Aotea Sandstone and Orahiri Limestone were being deposited. Lateral changes in facies older than the Aotea Sandstone are not so pronounced, but nevertheless similar trends are known. For example, sandstones and conglomerates are minor constituents of the Coal Measures in the north, but form the bulk of those at Mangapehi.

Lateral distribution shows the normal change of sandstone to mudstone as deposition took place farther from the shoreline. It also shows that coarse, flaggy limestones are formed under near-shore conditions. This is particularly noticeable at two horizons—namely, the Orahiri Limestone and the Elgood Limestone member of the Glen Massey Formation. Although the Elgood Limestone is exposed near Te Akatea, its presence in the northern part of the Waikato Coalfield is unusual. Where, as in the southern part of the coalfield, the underlying Mangakotuku Siltstone and Coal Measures are thin or absent, the Elgood Limestone is very persistent and attains a maximum thickness of 100 ft. All the flaggy limestones are formed of comminuted shell fragments and coarse sand, and are often falsely bedded. Thus, both lateral distribution and lithology show their shallow-water origin.

As with isopachs, lack of information precludes finer detail than that shown in the facies maps of Figs 11 and 12. At Karamu (Fig. 1), there has been local coarsening, the Dunphail Siltstone, Glen Massey Sandstone, and Whaingaroa Siltstone being slightly coarser than they are at Te Akatea to the north and at Okoko to the south.

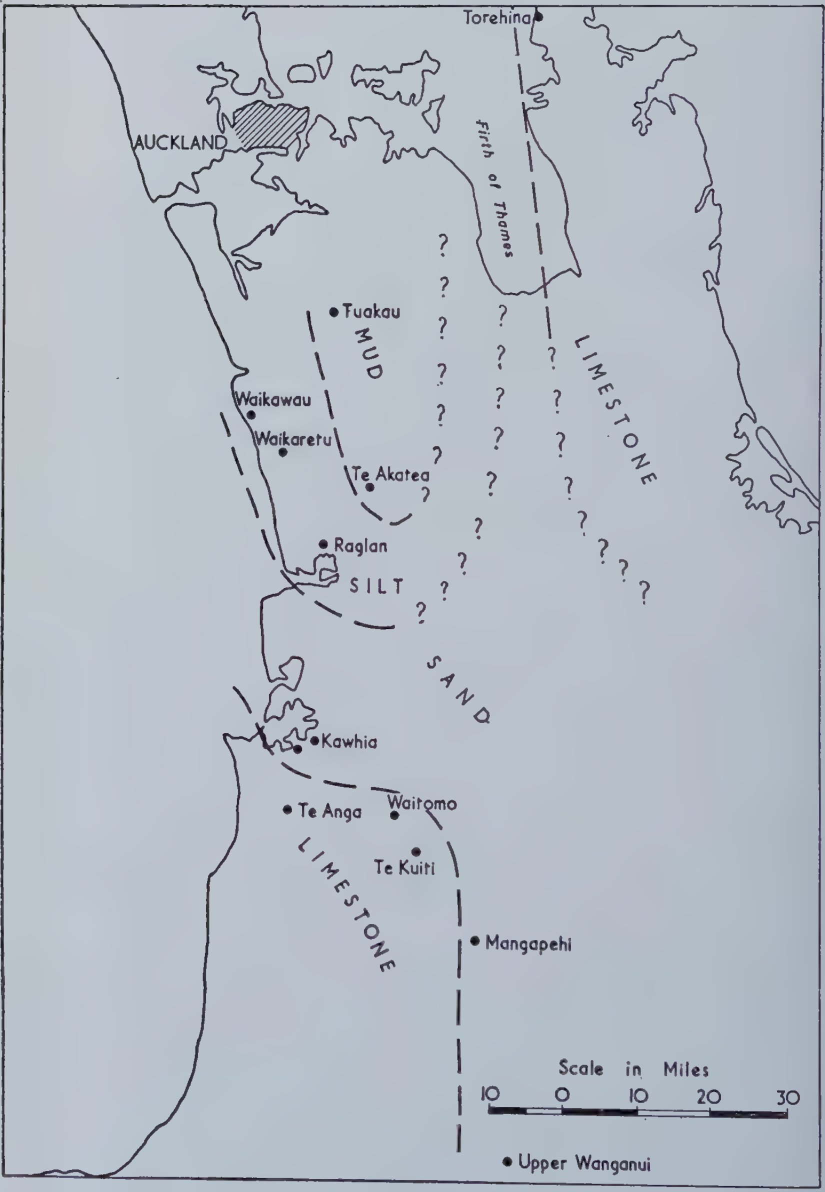

FIG. 12.—Distribution of facies during the Duntroonian.

Facies Control of Faunas

Duntroonian-like microfaunas from the calcareous siltstone horizons and macrofaunas from the sandstones within the Mangakotuku Siltstone contain rare Foraminifera and ostracods of Runangan affinities which probably lived in a warm shallow-water environment (Mr N. de B. Hornibrook, pers. comm.). Mr N. de B. Hornibrook has provisionally determined these microfaunas as "basal Whaingaroan".

Duntroonian-like faunas are also present in the shallow-water Aotea Sandstone, but these can be differentiated from true Duntroonian, and Mr N. de B. Hornibrook (pers. comm.) is now able to recognize two shallow-water faunas of lower and of upper Whaingaroan age.

These results have been the outcome of co-operation between field geologists and paleontologists and show the value of mapping in formations rather than mapping in age units. Paleontologists are always aware of facies control, but, unless mapping is done by formations, such facies control may not become apparent and thus, not only might error be perpetuated, but much information of value could be lost.

EASTERN LIMITS OF SEDIMENTATION

Lack of Tertiary remnants will always leave the eastern limits of deposition of the Te Kuiti Group in doubt. However, in the north, both Coal Measures and the Mangakotuku Siltstone thin eastwards. As this thinning is most likely due to overlap, transgression probably occurred to the east as well as to the west and south. Further evidence is supplied by the only known outcrop in the east at Torehina in the northern portion of the Coromandel Peninsula (Brothers and Mason, 1954; Kear, 1955). Here Coal Measures are overlain by 150 ft of calcareous siltstones of Duntroonian age which are in turn overlain by a thick flaggy limestone.

GEOLOGICAL HISTORY

The pre-Tertiary landmass in the South Auckland area was not a peneplain. Abrupt thickening and thinning of the Coal Measures shows that the landscape may have been no more than sub-mature. Coal Measures, formed in the low-lying parts of this land, appear confined to a north-south trending depression formed in pre-Coal Measure times. The thickest and most extensive Coal Measures were deposited during Arnold times within land-locked depressions and formed the northern part of the Waikato Coal Region. Initially, in the subsequent transgression, anaerobic conditions persisted during deposition of the Mangakotuku Siltstone, which was characterized by penecontemporaneous leaching of its calcium carbonate content. Continued transgression reduced the land-locked nature of the inland seas so that alternating anaerobic and aerobic conditions caused the interbedded calcareous and uncalcareous nature of the upper Mangakotuku siltstones. Further transgression produced more open-sea conditions, so that, from then on, aerobic conditions prevailed.

Clastic material consisted of both sand and mud which had a lateral distribution shown in Figs 11 and 12. Halts during transgression allowed deposition to reach wave-base, so that sands were deposited farther off-shore than normally. In this way, sandstones became interbedded with mudstones. Finally, as transgression proceeded, areas that persisted as land were reduced in size, and supply of clastic material decreased, so that eventually the widespread, relatively thick Otorohanga Limestone was produced. Precursors of this limestone were not so well developed, although they became more persistent laterally as the supply of clastic material was reduced. Reduction of clastic sediments is also reflected in the calcium carbonate content of the Whaingaroa and Te Akatea siltstones. The latter is the younger, and has a much higher percentage of lime together with cherty bands at the type locality. It is almost a limestone and could well have passed northwards into an offshore foraminiferal limestone.

Transgression of the sea was caused mainly by regional subsidence, or eustatic rise in sea-level, as is shown by migrating shorelines (Fig. 9) and overlap (Fig. 2). In the present state of knowledge of formation thicknesses, downwarping is not necessary to explain the isopach distribution, which can be adequately explained by overlap.

Transgression was interrupted at times either by stillstand or regression of the sea, or by slight differential uplift. These periods are shown by disconformities at the base of (1) the Dunphail Siltstone, (2) the Aotea Sandstone (locally), and (3) the Orahiri Limestone.

Deposition of the Te Kuiti Group finally ceased when tectonic activity produced (1) an angular unconformity between it and younger sediments and (2) uplift of the source province from which the subsequent clastic sediments were derived.

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GEOLOGICAL INVESTIGATIONS IN SOUTH VICTORIA LAND, ANTARCTICA

PART II—GEOLOGY OF UPPER TAYLOR GLACIER REGION

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Summary

Immediately south of the upper Taylor glacier lies a small ice-free area including three minor dry valleys provisionally named the Arena, Beacon, and Turnabout. The rocks exposed are Beacon sediments intruded by dolerite sills and dykes. Three lithological members are recognized in the sediments. Two petrographically distinct types of dolerite are present. Glacial and post-glacial erosion has produced a land form controlled by the lithology and structural relations of the sediments and dolerite.

INTRODUCTION

During late January and early February 1958, field camps were established with the aid of a United States Navy helicopter at the following ice-free localities in the vicinity of the upper Taylor glacier (Fig. 1): (1) The north side of the Taylor glacier beneath North West Mountain at approximately long. 160° 50′ E and lat. 77° 42′ S; (2) a deglaciated valley provisionally named the Beacon Valley opening into the southern side of the upper Taylor glacier, approximately long. 160° 50′ E and lat. 77° 48′ S; (3) a small dry valley on the east flank of Mt Knobhead, approximately long. 161° 40′ E and lat. 77° 55′ S (Fig. 2). Detailed geological examinations were carried out from these camps at altitudes ranging from 4,300 ft to 7,300 ft. The rocks consist of nearly horizontal Beacon sediments intruded by dolerite sills and dykes (Fig. 3). To the east, outside the area examined, the sediments rest on basement granite which is intruded by dolerite sills (Ferrar, 1907).

The Taylor and Ferrar glacier areas were examined geologically during Scott's National Antarctic Expeditions of 1901–04 and 1910–14, Shackleton's British Antarctic Expedition of 1907–09, and the Trans-Antarctic Expedition of 1956–58. The geological investigations of the upper Taylor glacier form part of an Antarctic project by Victoria University of Wellington.

GLACIATION AND PHYSIOGRAPHY

The upper Taylor glacier flows eastwards from the Antarctic ice plateau to the Kukri Hills, where it bifurcates. The northern branch

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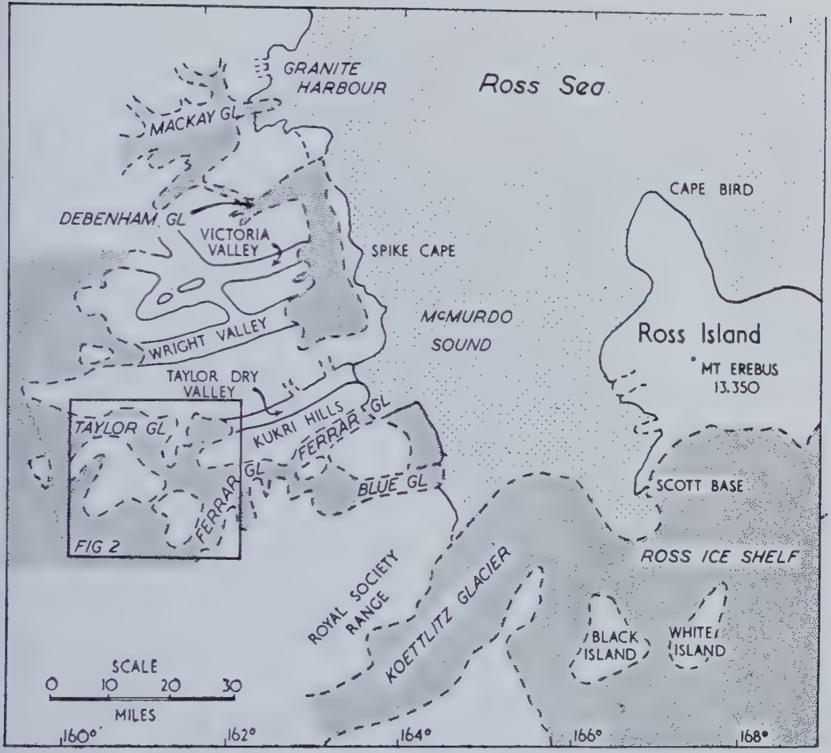

Fig. 1.—Locality map of western coast of McMurdo Sound, South Victoria Land.

ends abruptly, the former glacier course being represented by the Taylor Dry Valley. The southern branch joins the Ferrar glacier, flowing from its névé in the south-west (Fig. 2).

The Taylor glacier, margined by high ice cliffs along much of its course, is noticeably underfit. In the vicinity of Pyramid and North West Mountains lateral extensions of the glacier extend into otherwise ice-free valleys and cirques. Several ice falls break the surface of the glacier.

The ice-free areas examined occur in two partially deglaciated ranges immediately north and south of the upper Taylor glacier. In the vicinity of North West Mountain, sediments have been almost completely stripped from above a dolerite sill, the near flat surface of which now caps the range at 7,000 ft above sea-level. The steep walls of this range are formed by coalescing cirques, the more easterly of which are nearly ice free (Fig. 4).

East of North West Mountain, cirques have cut back more deeply to form isolated steep-sided peaks—the Inland Forts of Ferrar (1907).

The 8,500 ft range bordering the south side of the upper Taylor glacier is completely surrounded by ice. Deglaciation is most extensive

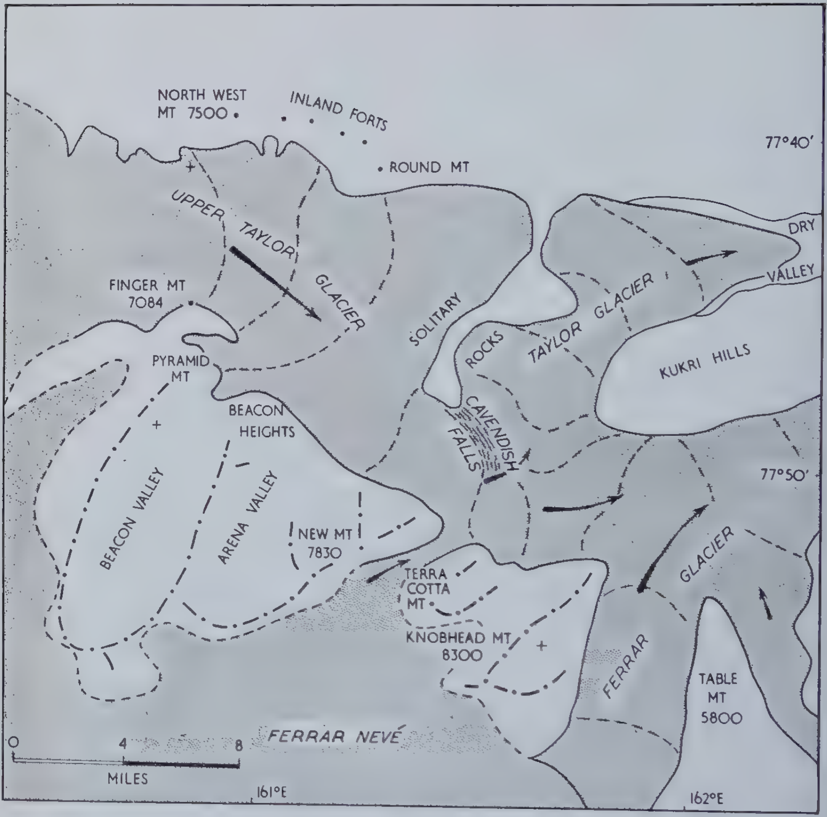

FIG. 2.—Map of upper Taylor glacier area.

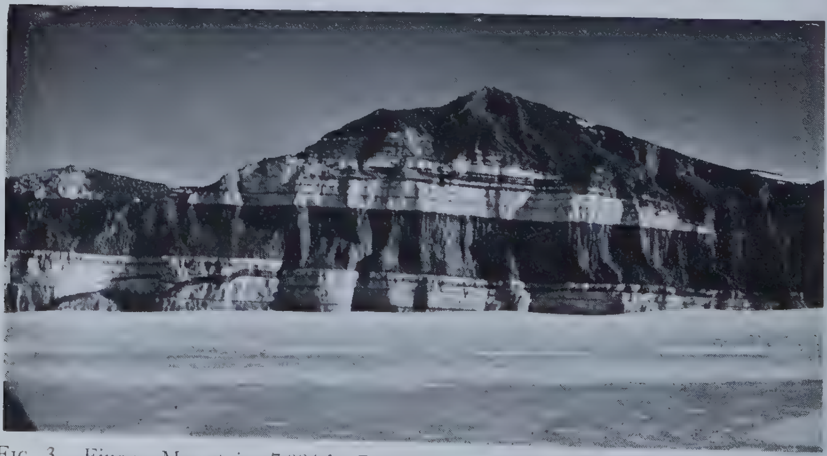

FIG. 3.—Finger Mountain, 7,084 ft. Dolerite sills intruded into Beacon Sandstone. The lower sill is approximately 250 ft thick.

in the west, where the Arena, Beacon, and Turnabout valleys that open on to the Taylor glacier are largely ice free. A small glacier from the Ferrar névé flows through the range down to the Taylor glacier (Fig. 2).

In the past, several glaciers followed parallel courses, and the former Arena Valley glacier received most of its ice from the Ferrar névé.

GEOMORPHOLOGY OF BEACON VALLEY

The geomorphology of Beacon Valley, being representative of the three valleys, is described in some detail.

The moraine of the valley floor emerges from beneath ice cliffs of the remnant Beacon glacier at the valley mouth and rises steadily for two and a half miles until it attains its maximum altitude of approximately 4,750 ft. From this point, it continues up valley in a series of gentle undulations to terminate in a shallow basin beneath coalescing valley end cirques.

To the west, the floor abuts a steep glacier-cut valley wall. A prominent moraine shoulder, its surface about 5,000 ft above sea-level, extends along the eastern side of the valley (Fig. 5) and extends back to the eastern cirque floors. Moraine material varies in size from boulders more than 6 ft in diameter to coarse sand. Dolerite is predominant in all moraine and scree deposits, even to the apparent exclusion of sedimentary material in many places. This suggests that the Beacon sediments, upon entering the screes or moraine, are quickly reduced to sand. A small proportion of the moraine consists of erratics foreign to the area. The majority of these are coarse acid plutonics similar to those recorded by Woolnough (1916) and Webb and McKelvey (1959). The degree of post-glacial modification of the moraine by sand abrasion and frost heaving varies throughout the valley. On the valley floor, the moraine shows only a moderate degree of wind abrasion, but frost polygons (Fig. 6) are well developed, especially where the floor undulates up valley towards the terminal cirques. The polygons, up to 25 ft across, have slightly concave surfaces and are bounded by peripheral troughs as deep as 4 ft.

With one exception, material on the ascending slope of the moraine shoulder shows little sign of wind abrasion. Starting near the valley mouth, a shallow trough about 30 ft wide descends down the slope of the shoulder in an up-valley direction for about three miles. The floor of this trough is strewn with small ventifacts (Fig. 7).

Frost polygons on the surface of the moraine shoulder are subdued in relief, their peripheral troughs either lined or filled with small rock fragments and sand.

The western, eastern, and southern valley walls differ considerably. The western wall at the valley entrance rises steeply about 1,500 ft from the valley floor. Cirques, cut back into this wall, have floor entrances about 800 ft above the level of the valley mouth. The cirque floors become less well defined towards the head of the valley and merge with the rising valley floor. The cirques commonly broaden out near their back walls, especially where they are cutting into sedimentary material. Cirques initially cut into horizontal dolerite sills generally have steep sides and are relatively narrow. As development progresses, ice near the back wall may start to erode the softer overlying sediments. Extensive lateral and backward cirque development takes place in the sediments, with only minor downcutting into the resistant dolerite. Thus a marked step develops between the front and back of some cirques. Cirque action on dolerite and Beacon sediments produces sheer rock walls. During post-glacial erosion, the dolerite walls continue to weather back steeply and become blanketed with dolerite screes. Cirque walls of Beacon sediments become "terraced" (owing to their horizontal bedding), and lack extensive screes (Fig. 8).

The size and shape of cirques on the eastern side of the valley are largely controlled by dolerite, although here it is much less abundant than in the west. The cirque mouths open on to the surface of the moraine shoulder, which probably obscures a reduced eastern valley wall. Cirques, when cut back into predominantly sedimentary rocks, are long and narrow, owing to rapid headward erosion in the soft sediments. Cirques excavated in sediments intruded by an appreciable amount of dolerite are shallower and generally smaller. This is due to the dolerite being more resistant to erosion and also providing a thick blanket of durable moraine, which is eventually deposited on the cirque floor by the receding ice. Some cirques contain shallow frozen tarns on their floors and dwindling patches of ice near their heads.

Several cirques, some coalescing, terminate the valley to the south. The floors of these cirques are level and continuous with the floor of the valley.

The altitudes and profiles of the valley divides are controlled by their rock types. Beacon sediments, which form much of the eastern divide, produce a flat-topped profile at approximately 6,500 ft.

Dolerite-capped peaks rise to more than 8,500 ft on the western divide. The south-west part of the divide is capped by an ice field, probably an extension of the Ferrar névé or the inland ice plateau. This ice field supplies ice to the remnants of the Turnabout Valley (Fig. 5).

RETREAT OF THE BEACON VALLEY GLACIER

From consideration of the valley moraine deposits, some conclusions regarding the ice withdrawal have been made.

The valley floor moraine is appreciably less modified by wind abrasion than the moraine on the shoulder or that within the eastern cirques. This indicates that ice covered the valley floor after the moraine shoulder was formed and the eastern slopes became ice free. The ice has now retreated back to the ice cliff overlooking the valley in the south-west.

This suggests that the last glacier ice to occupy the full length of the valley was essentially supplied by the ice field to the south-west. The glacier ice blocking the valley mouth represents the last remnants

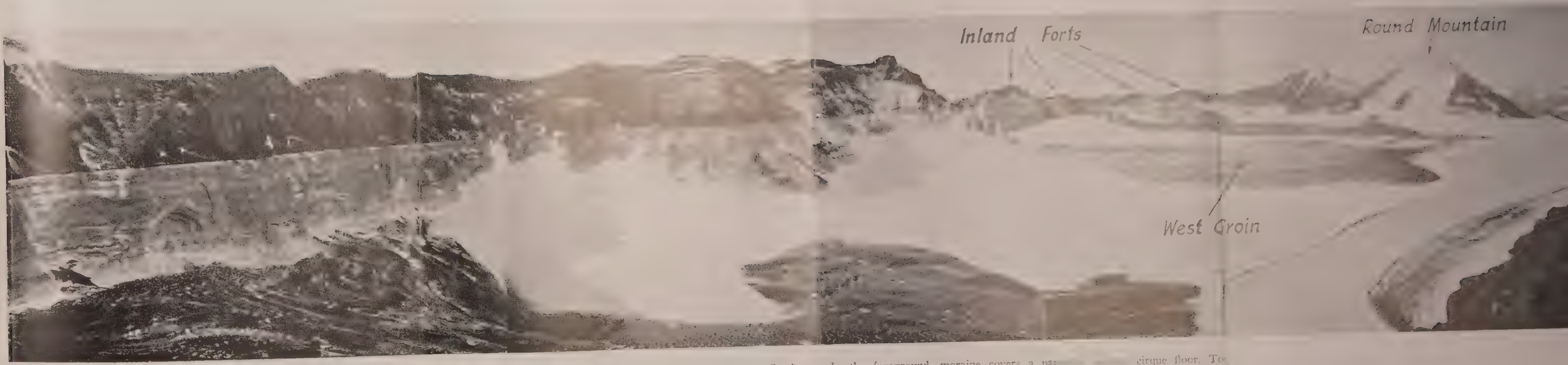

Fig. 4.—View east from North West Mountain. A dolerite sill caps Beacon Sandstone In the foreground, moraine covers a pa[illegible] cirque floor. To the right, West Groin disappears beneath Taylor glacier ice, which carries some lateral m[illegible]

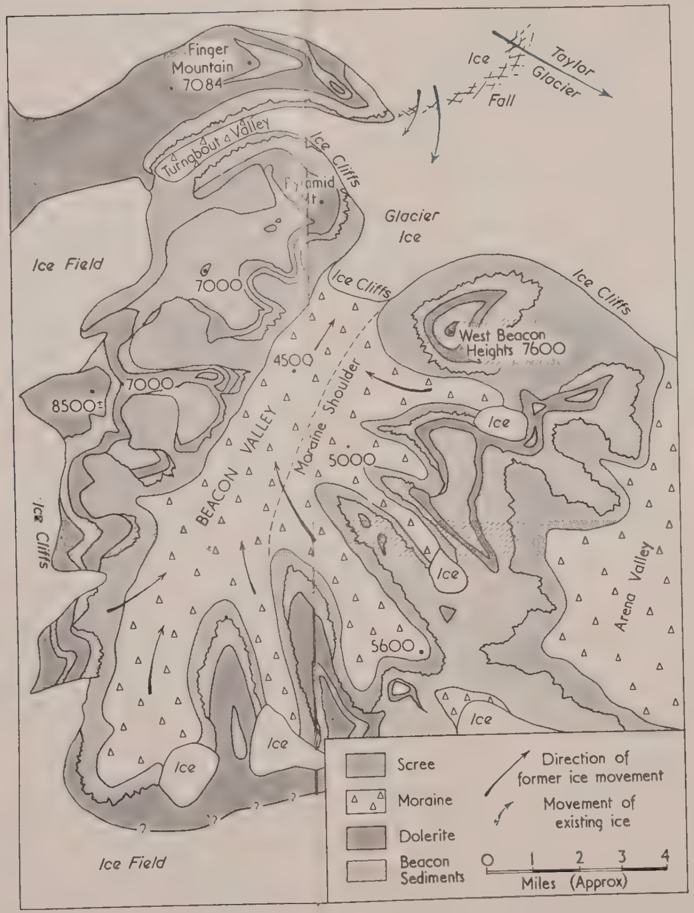

Fig. 5.—Sketch map of Beacon Valley.

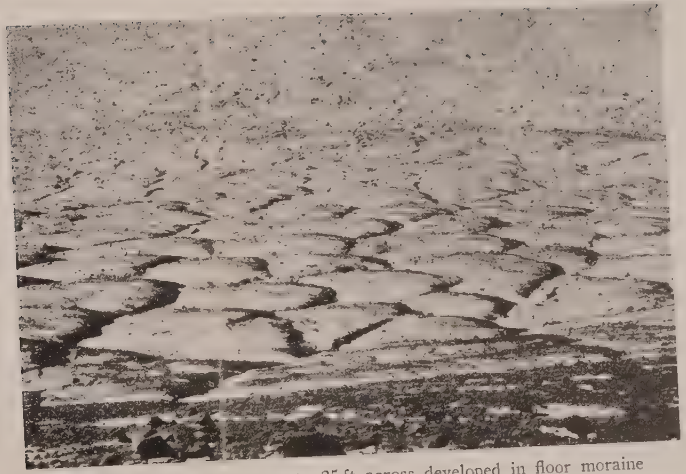

Fig. 6—Frost polygons up to 25 ft across developed in floor moraine of a small valley east of Mt Knobhead.

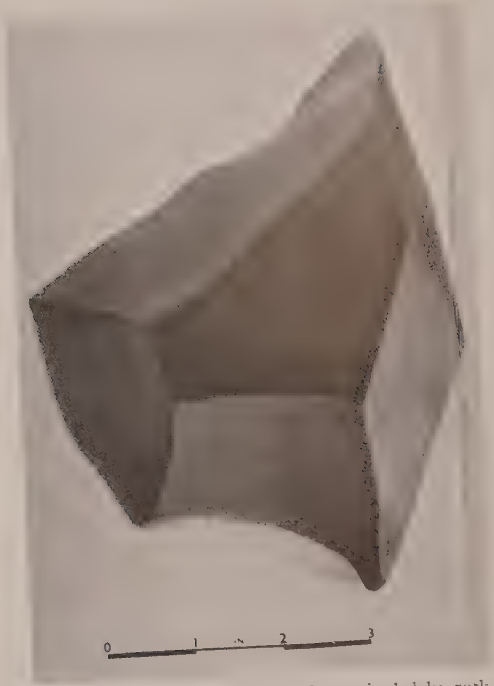

Fig. 7.—Ventifact formed from fine-grained dyke rock.
—*M. D. King, photo.*

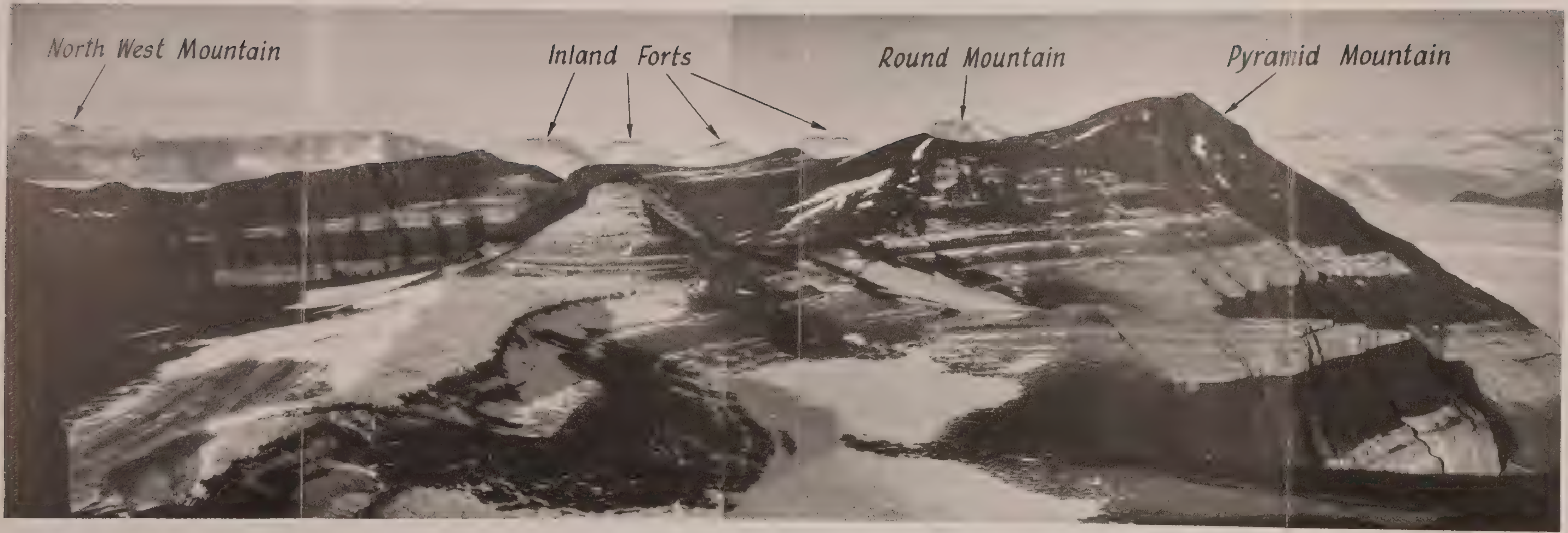

Fig. 8.—View looking north from western divide of Beacon Valley. On the left is the steep glacially cut ice wall of the Turnabout Valley. Taylor glacier ice is on the extreme right. In the foreground are prominent terraces of Beacon sediments.

of the Beacon glacier. Thus it follows that the initial ice-free portion of the valley floor resulted from the simultaneous northward and southward retreat of the Beacon glacier ice. This is in accordance with the present stage of recession in the Turnabout Valley, where only the middle reaches are ice free and the ice source is to the south.

The remnant glacier ice blocking the valley mouth merges imperceptibly into the higher ice of the Taylor. But any flow of Taylor ice into the mouth of the Beacon is at least fully compensated by ablation, as there is no evidence of present-day ice movement up the Beacon Valley.

THE BEACON SANDSTONE

The Beacon Sandstone (Ferrar, 1907) crops out widely in South Victoria Land and consists of arkosic to quartzose sandstones often interbedded with conglomerates, shales, coal, and, rarely, thin limestones (Ferrar, 1907, 1925; Prior, 1907; David and Priestley, 1914; Mawson, 1916; Debenham, 1921). Similar sediments are known from Adelie Land (Mawson, 1940) and the Queen Maud Ranges (Gould, 1935). It has been suggested that all these sediments be incorporated into a Beacon System and the type rocks of South Victoria Land termed the Beacon Sandstone Group (Harrington, 1958). For convenience, the sediments discussed in this paper are considered as a "Beacon Formation". Beacon sediments studied so far have proved to be only sparsely fossiliferous. Definite upper Devonian fossils (Woodward, 1921) and later Paleozoic fossils (Seward, 1914; Edwards, 1928) have been described. The age range of the sediments beyond either of these limits is unknown. No useful fossils were found by the writers.

Approximately 2,000 ft of Beacon sediments were examined, the lowest of which are about 1,500 ft above the Basement–Beacon contact. Beacon sediments younger than those discussed occur in the area, but were not examined. Three members of differing lithology are recognized in the Beacon Valley. All the Beacon sediments dip gently to the west.

Section 1 Mile South of Pyramid Mountain, West Side of Beacon Valley.
Dolerite excluded.

Member C	Thickness ft.
Cross-bedded fine-grained sandstone	20
Cross-bedded medium-grained sandstones with abundant carbonaceous material	75
Cross-bedded fine-grained sandstones. No obvious carbonaceous material	40
Sandstones and interbedded shales. Carbonaceous. Occasional thin quartz pebble bands in thin pure sandstones	145
Massive sandstone containing thin pebble bands	40
Fine-grained sandstones with thin carbonaceous shales	55
Coarse dark grey sandstones	60
Contorted black shales	2
Massive sandstones with thin shale bands	55
Cross-bedded sandstones, abundant carbonaceous material	35
Cross-bedded sandstones, no obvious carbonaceous material	40

Member B

Light green sandstone, with polygonal suncracks up to 2 ft in diameter	2
Green sandstones interbedded with white sandstones	2
White sandstone	1
Green sandstones and siltstones. Gradational base	10
Red siltstones containing irregular sharply defined green patches, and carbonate nodules towards the base	35
Green siltstone	6
Red siltstone	3
Green siltstone	1

Member A

White, buff, and light grey sandstones. Commonly cross bedded. No carbonaceous material	>1400

The carbonaceous material in member C appears to be of plant origin. Carbonized twigs commonly occur imbedded in light grey sandstones. Many beds of member C are micaceous.

Sediments resembling those of member B occur 16 miles east of Beacon Valley on the east flank of Mt Knobhead between points B9 and B9A of Mulock. About 50 ft of interbedded red, green, and white sandstones occur behind terraces on the sides of a small ice-free valley (Fig. 9). The red sandstones are commonly cross bedded and are at places overlain by thin green sandstones featuring fossil suncracks. Pale green sandstones may be interbedded solely with white sandstones. Where a red sandstone is underlain and overlain by white sandstone,

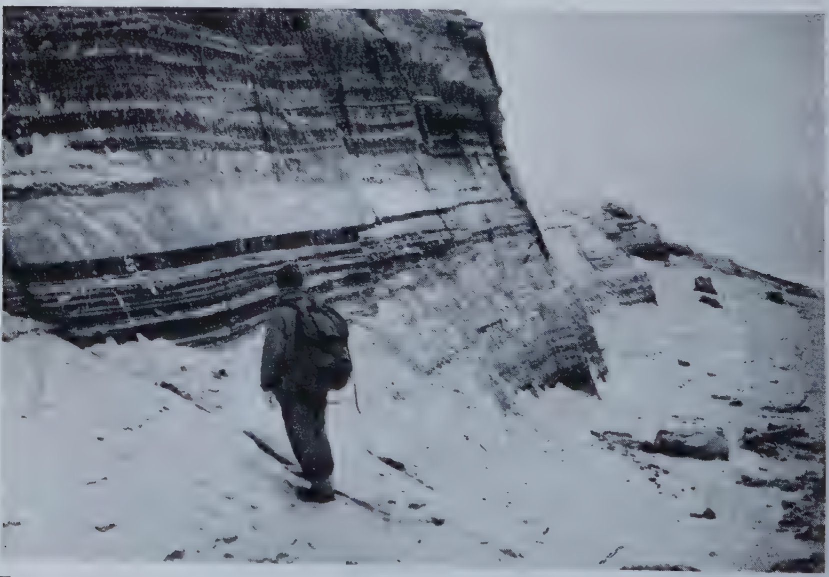

Fig. 9.—Interbedded red, white, and green sandstones exposed east of Mt Knobhead.

the upper contact is sharp, the lower gradational. Irregular tubular infillings of white sandstone half an inch in diameter penetrate down into the red sandstones and are spread thickly and evenly throughout them. Weathering out of some white sandstones associated with the red beds are vertical cylindrical structures up to 9 in. in length and 3 in. in diameter.

Beds similar to member A occur at North West Mountain. They are white and grey sandstones, generally weathered to a buff colour on the surface. Individual beds range in thickness from a few inches up to several feet and are usually cross bedded. They contain flattened ferruginous concretions up to 2 ft in diameter and abundant worm casts. These rocks appear to be identical with those described by Ferrar (1907) from the Inland Forts and West Groin (Fig. 7).

The Ferrar Dolerites

General

Dolerites occur throughout much of East Antarctica, being recorded at Bungers Oasis (Ravich and Soloviev, 1957), Adelie Land (Browne, 1923), South Victoria Land (Ferrar, 1907; Webb and McKelvey, 1959), and in the Queen Maud Ranges (Gould, 1935).

In South Victoria Land, the dolerites occur as dykes and sills in both the crystalline basement and the overlying Beacon sediments. Some sills within the basement are at least 1,500 ft thick. Most sills within the Beacon sediments are less than 600 ft thick. The petrography of South Victoria Land dolerites has been described by Prior (1907), Benson (1916), and Webb and McKelvey (1959). It has been suggested that the dolerites of South Victoria Land be incorporated into the Ferrar dolerite formation (Harrington, 1958).

Structure

The dolerites are intruded along horizontal bedding planes and into vertical fracture planes in the sediments.

Several sills climb to higher levels by way of the vertical fracture planes and then again follow the horizontal bedding. This "stepping" may be repeated several times. Where the horizontal and vertical components are small, thick sills appear to cut obliquely across the bedding of the sediments. Dolerite stringers from large sills commonly penetrate the underlying sediments in step-like fashion. Large xenoliths of Beacon sandstone up to 50 ft in length occur near the lower margins of some sills (Fig. 10). Even where dolerite sills are intruded in profusion, the Beacon sediments still essentially retain their original horizontal attitude.

Contact metamorphism in the sediments is restricted to a few inches in width.

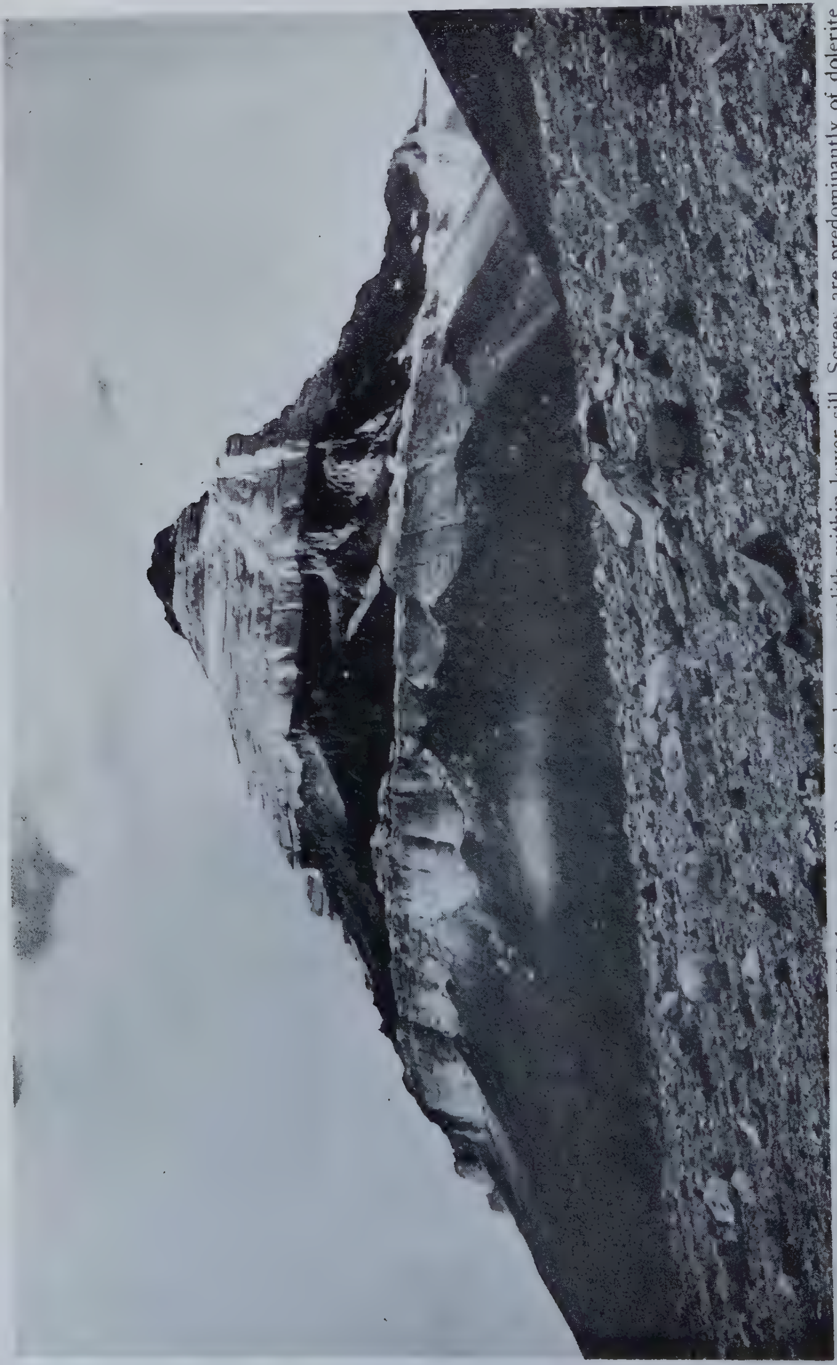

FIG. 10.—Mt West Beacon Heights, 7,800 ft approx. Beacon Sandstone xenolith within lower sill. Screes are predominantly of dolerite.

The sills display well-developed columnar jointing. Horizontal joint planes, best developed near the contacts, are less prominent. Dolerite dykes cut both sills and sediments and display a fine but highly developed columnar jointing normal to the dyke contacts.

Petrography

Two petrographic dolerite rock types are recognizable in hand specimens. The coarser type was seen only immediately east of Mt Knobhead, capping point B9A of Mulock. It resembles the Mt Knobhead moraine specimen described by Benson (1916) and dolerites from Victoria Dry Valley (Webb and McKelvey, 1959).

The principal minerals present are plagioclase sub-ophitically associated with monoclinic and orthorhombic pyroxene. The plagioclase ranges in size from 1 mm to 1·5 mm, the pyroxenes from 1·5 mm to 4 mm. Plagioclase forms 48·7% of the rock and the pyroxenes 47·2%.

The pyroxenes are hypersthene, augite, and pigeonite.

The hypersthene ($2V = 68^\circ$ En. $= 70$) displays a prominent Schiller structure and is commonly intergrown with augite.

Augite ($2V = 47^\circ$ to 51°, $Z \wedge C = 37^\circ$) also occurs separately and usually shows alteration to chloritic minerals along cleavages. Iron ore rims and penetrates some augite crystals.

Pigeonite occurs separately as small crystals or surrounds hypersthenes. Some pigeonite is nearly uniaxial, but other grains have optic axial angles up to 37°.

The plagioclase is mainly calcic labradorite. It is well zoned and twinned on the albite and carlsbad laws. Small amounts of quartz and plagioclase micrographically intergrown fill interstices between feldspar crystals.

The other petrographic type is a finer grained green-black rock, usually with a thin ferruginous coating due to weathering. The main minerals present are plagioclase and clinopyroxene. Sub-ophitic texture is usual.

The pyroxene is augite ($2V = 42^\circ$ to 54°, $Z \wedge C = 44^\circ$, and is usually extensively altered to fibrous chloritic minerals. Iron ore minerals rim many augite crystals.

The plagioclase (An_{70}), twinned on the albite and carlsbad laws, is extensively zoned. Considerable amounts of fine-grained mesostasis occur in the dolerite. This contains recognizable quartz, plagioclase, apatite, and chlorite. The mesostasis is usually heavily studded with small grains of iron ore.

Occasionally, small micrographic intergrowths of quartz and feldspar have been noted. Some chlorite is present interstitially.

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SECONDARY FAULTING AND TRANSCURRENT SPLAY-FAULTING AT TRANSCURRENT FAULT INTERSECTIONS

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Summary

Two principles are put forward to explain secondary faulting and transcurrent splay faulting at the intersections of clockwise with anti-clockwise transcurrent faults. The first is based on the convergence and divergence of material respectively in the compressional and tensional sectors between the intersecting transcurrent faults. The second principle is based on the opposed sense of lateral displacement at the intersection of transcurrent faults. Either or both can be used to explain given examples.

Principle of Convergence and Divergence of Material

The directions of displacement in the sectors between clockwise and anti-clockwise transcurrent faults are shown in Fig. 1. In two opposite sectors (γ) the directions of displacement converge towards the fault intersection, while in the remaining two opposite sectors (δ) the directions of displacement diverge from the fault intersection. The convergence of material causes a local shortening and local compression, and the divergence of material causing local lengthening, engenders local tension. The displacements, causing the local convergence and divergence of material, therefore engender local compression and tension in adjacent sectors irrespective of the regional stress conditions.

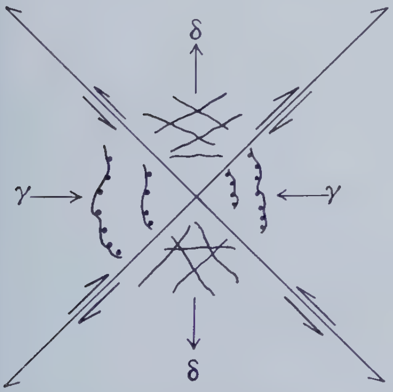

Fig. 1.—Convergence and divergence of material at clockwise and anti-clockwise transcurrent fault intersection.

Applying this principle to compressional regions, local tension in two opposite tensional sectors reduces the regional compression, whereas in the compressional sectors the local compression adds to the regional compression. Hence, in areas of regional compression, addi-

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tional compression generated in the compressional sectors can cause secondary folding, thrusting, and reverse faulting in those sectors.

By analogy, in tensional regions, because of the addition of local tension to the regional tension, the movements on the intersecting clockwise and anti-clockwise transcurrent faults can cause normal faulting with associated dike formation and volcanic activity in their tensional sectors. In the compressional sectors the local compression reduces regional tension.

Principle of Opposed Sense of Lateral Displacement

This principle is illustrated in Fig. 2. In Fig. 2a clockwise and anti-clockwise transcurrent faults intersect, producing two opposite compressional sectors (γ) and two opposite tensional sectors (δ). A movement occurs along the clockwise transcurrent fault, as indicated by arrows. The resulting displacement is shown in Fig. 2b, where the anti-clockwise transcurrent fault is offset in clockwise sense. The next movement occurs along the anti-clockwise transcurrent fault, again as indicated by the arrows. At the intersection the direction of movement is directly opposite, causing a local compression (c). One of the possible displacements is shown in Fig. 2c where the clockwise fault is offset in anti-clockwise sense, and a splay fault has formed along the anti-clockwise fault to facilitate the displacement along that fault. This process of alternate clockwise and anti-clockwise lateral faulting is repeated in Figs 2d, e, and f, in every case producing directly opposite directions of movement, causing repeated local compression. This compression occurs invariably, as shown in Fig. 2, in the compressional sectors (γ).

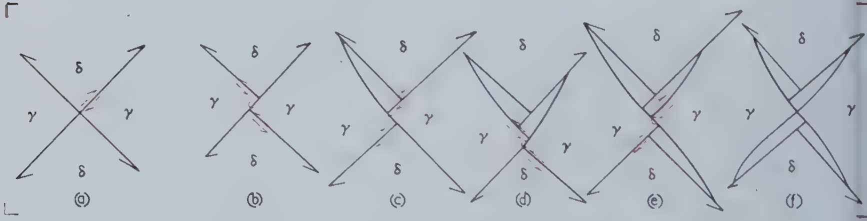

Fig. 2.—A series of successive alternating clockwise and anti-clockwise lateral displacements of and along transcurrent faults.

The movement can be taken up by drag-like curving of the other transcurrent fault. After repeated movements this drag will become too large to be maintained, and a splay fault will occur and will take over much of the transcurrent displacement.

Applying this principle to compressional regions, local compression in the compressional sectors increases the total compression, while the regional compression in the tensional sectors remains unaltered.

Any secondary compressional features, like reverse faulting or folding, can therefore be expected to occur in the compressional sectors of intersecting transcurrent faults.

Applying this principle to tensional regions, local compression will reduce the regional tension in the compressional sectors, but the regional tension in the tensional sectors will not be affected. Any secondary tensional features will therefore appear in the tensional sectors.

EXAMPLES

The fault pattern in the compressional region of California is given as an example in Fig. 3 (after Hill, 1955). In this complex pattern the clockwise transcurrent San Andreas Fault intersects the anti-clockwise transcurrent Garlock—Big Pine Fault. The Pleito, Frazier, Pine Mt, San Cayetano, Oak Ridge, San Susana, and Sierre Madra faults are all thrusts and are entirely confined to the two compressional sectors (γ), while in the two tensional sectors (δ) secondary reverse faulting is completely absent. Reverse faulting can be explained by both principles. According to the opposed sense of displacement principle, the

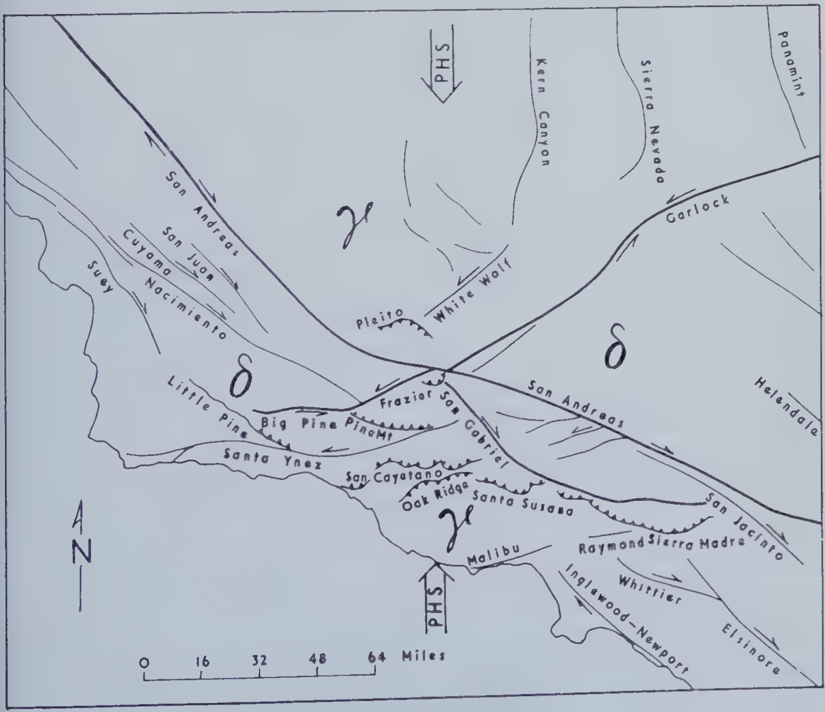

FIG. 3.—The active fault pattern in South California (after Hill, 1955).

Pleito and Frazier thrusts will be the youngest secondary features present. The San Gabriel, San Jacinto, White Wolf, and other faults are transcurrent splay faults.

Hill and Dibblee (1953, p. 457) have explained the "strain" pattern in this region by favouring a northeast-southwest anti-clockwise couple out of the three possible effective orientations: north-south oppositional forces (PHS); or a northeast-southwest anti-clockwise couple; or a northwest-southeast clockwise couple.

If the northeast-southwest couple were indeed the dominant force, then the Big Pine—Garlock anti-clockwise transcurrent faults should be the dominant ones. But this is not so, as the major displacements occur along the clockwise transcurrent San Andreas fault. The authors even propose, in the same paper (*op. cit.*, p. 449), a 350 mile lateral displacement along this fault since the Jurassic. Also, the Big Pine—Garlock fault should, with a northeast-southwest couple, have a normal component. This again is not the case as this anti-clockwise fault has a reverse component. Hill and Dibblee (*op. cit.*, p. 452) do not regard the reverse component as being significant.

These authors base their preference for a northeast-southwest couple on the presence of northwest-trending folds in the marine sediments of Miocene age. These folds may very well either be drape folds over blockfaulted basement, or local folds (see Lensen, 1958, p. 584-6) induced by the reverse component of the San Andreas Fault. In either case the folds need not be true compressional folds in the sense that they occur normal to the regional stress, irrespective of whether this regional stress is of the pure shear (PHS, etc.) or the simple shear (couples) type.

As a regional tensional example the fault and lode pattern of the Tavua Goldfield in Fiji is shown in Fig. 4 (after Blatchford, 1953). The normal fault and lode pattern is confined to the tensional sectors (δ), and the anti-clockwise transcurrent fault shows both drag-curve and splay features.

In general, the fact that lode formation is confined to the tensional sectors may be of economic importance in prospecting and mine planning.

The presence of isolated volcanoes apparently not associated with volcanic belts may be explained by the first principle.

ABSOLUTE TRANSCURRENT MOVEMENT

It should be noted that, in both compressional and tensional regions, secondary faulting is confined not only to the corresponding sectors, but generally to one of the sectors only.

This phenomenon is difficult to explain unless it is assumed that rock that is intermittently subjected to movement fractures more easily than rock that remains stationary. If this assumption is applied to the fracture pattern in California (Fig. 3), then the south-eastern side of

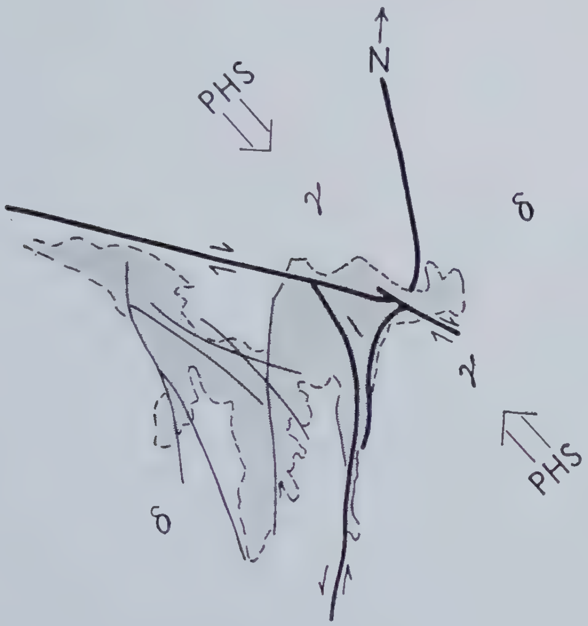

FIG. 4.—Fault and lode (shaded) pattern in the Tavue Goldfield, Fiji (after Blatchford, 1953).

the Big Pine—Garlock Fault has moved anti-clockwise and the north-western side remained nearly stationary, while along the San Andreas Fault the south-western side has moved clockwise and the north-eastern side has remained nearly stationary. The southern compressional sector has therefore experienced both the clockwise and anti-clockwise lateral movement and should therefore show the most fractures. This is the case. Accepting these actual movements along the transcurrent faults, it becomes evident that the Pacific side of California moves while the continental side remains approximately stationary, thus confining and defining the "mobile belt" more clearly. This conclusion is compatible with current theories of anti-clockwise rotation of the entire Pacific. (Benioff, 1957, St. Amand, 1957).

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THE SUGAR LOAF INTRUSIONS NEAR NEW PLYMOUTH

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Summary

Observations on the New Plymouth Sugar Loaf Islands and their framework indicate that the dacitic intrusions "protruded" to the surface in a nearly solid state. They are on the summit of a much larger substructure with its greatest dimension in a north-east–south-west direction. Huge blocks of sedimentary sandy mudstone and pyroclastics were brought upwards on the flanks of rising plugs. Subsequently, these blocks slumped down the sides of the composite volcano, in all likelihood sub-aqueously. The protrusion of the Sugar Loaf plugdomes marks the latest phase of igneous activity, and post-dates the deposition of the Lower Pouakai Agglomerate. The movement terminated before the end of the deposition of the Upper Pouakai Sands.

The characteristics of accumulation and distribution of the Lower Pouakai Agglomerate suggest that neither the Kaitake centre nor the Pouakai centre was the main source for the pyroclastics.

HISTORICAL

Various views have been expressed by previous authors regarding the mechanism which could have produced the Sugar Loaf Islands. Clarke (1912) mapped the New Plymouth area and classed the islands as lavas. Hutton (1944) considered that they were remnants of steeply dipping cone-sheets. Interpretation of gravimetric and seismic investigations by Modriniak (Modriniak and Marsden, 1938) resulted in the idea that the Sugar Loaf intrusions belong to one major intrusion, with its centre north-west of Paritutu and ½ mile out to sea.

The concepts of the age of the intrusion also varied considerably. Clarke (1912) grouped the Sugar Loaves together with the agglomerates in his Lower Pouakai Series and emphasized the strong resemblance that exists between the andesitic agglomerates and breccias of Miocene age in the Whaingaroa Subdivision (North Auckland) and his Lower Pouakai Series. Marshall (*in* Hutton, 1944) considered that the Pouaikai rocks were older than the basalts of Auckland, but younger than the rhyolites of the Central Plateau of the North Island. Henderson and Ongley (1923) were among the first who noted the close resemblance between the intermediate volcanics of Whareorino (South Kawhia) and the igneous rocks of Paritutu, both in hand specimen and in chemical composition. Since contacts with Tertiary sediments were lacking, the Whareorino volcanics could only be dated as post-Jurassic. On the basis of andesitic fragments and crystals of hornblende and feldspar in the lower beds of Mohakatino "Series", Henderson and Grange (1926) inferred an Upper Miocene age for the Whareorino andesites.

A later petrographic examination of the Whareorino rocks by Hutton (1944) revealed that these rocks were dacites and, indeed, very similar to those of Paritutu. Based on the lack of any significant amount of tuffaceous or other igneous material in the sediments pentrated by the Devon-1 well, Hutton inferred the age of the Sugar Loaves to be post-Waitotaran, or at least post-Urenuian (discarded stage name)—i.e., early Pliocene or latest Mioceen.

Marwick pointed to the lack of any significant amount of agglomerate in the neighbourhood of Whareorino, and also that the more intimate grading between that dacites and the Mohakatino Formation is missing. He considered that the dacites might be younger than the Mohakatino beds, and either be Pliocene or Pleistocene in age.

Mr K. Glennie (pers. comm.) came to the conclusion that the volcano responsible for the supply of volcanic material in the Mohakatino was out in the Tasman Sea. This conclusion is based on the distribution of pyroclastic material in the Mohakatino Formation.

Stratigraphy and Petrography

The following table gives a generalized stratigraphical sequence as developed around New Plymouth.

Recent–Pleistocene

beach sands, boulders, etc.

———— erosion ————

tuff

———— erosion interval ————

Upper Pouakai Sands
Conglomerate Bed — time of Sugar Loaf intrusions

———— erosion interval ————

Lower Pouakai Agglomerate

Pliocene ———— slightly angular unconformity ————

Matemateonga Formation—sandy mudstones, clayey sandstones, shellbeds.
(formation not outcropping in this area. Here only found in wells and blocks at surface.)

The lithological units of Pleistocene age are described below in some detail.

Lower Pouakai Agglomerate: This agglomerate is composed of a chaotic mass of blocks, boulders, and finer material of mainly volcanic origin. The components of volcanic origin range from large boulder size to dust. In some outcrops, these components display such a remarkable uniformity in colour, texture, and composition that they are regarded as the disintegrated products, probably explosive, of the parent andesite. The bulk of the fragmentary material, however, is quite heterogeneous. Slight stratification is common, especially in the finer pyroclastics, but nowhere can the bedding be followed over a distance greater than some tens of metres.

Based upon this layering, much of the cliffed foreshore around New Plymouth, and as far south as Oakura, is composed of blocks of different sizes, each independently tilted. It seems that, after the deposition and subsequent consolidation of the volcanic material into a coherent, roughly stratified agglomerate, the area was broken up into blocks which were piled up on top of one another in chaotic re-arrangement. Many of the blocks measure several tens of metres for the two exposed directions. Blocks and rounded fragments of Pliocene sandy mudstones are locally mingled with the volcanics. One such block (mouth of Waireka Stream) measured 40 m by 60 m, and assuming that its third unexposed dimension is the smallest, it seems that the volume of this block may be between 50,000 and 70,000 cubic metres. Some of these blocks appear to have been in close contact with the volcanic material during movement, as volcanic fragments have been pressed into the mudstone.

Well preserved wood, lignite, and several boulders with shells were collected from the Lower Pouakai.

The surface of the agglomerate is irregular and variations in height occur over short distances. These "highs" are either primary and depositional (implying sub-aqueous transport, in which case some of the resulting accumulations of pyroclastics have not been eroded to the level of the surrounding agglomerate) or secondary, in which case up-arching caused by the intrusion of a semi-rigid igneous mass is implied. On the basis of the available evidence, the writer is strongly inclined to accept the second possibility as the more likely one, especially as andesitic plugs were invariably found near the location of agglomerate ridges.

Conglomerate Bed: The conglomerate bed is an irregular sheet of coarse detritus, derived during an erosion interval from the Lower Pouakai which it now overlies. Its components range in size from grit to large boulders and all are well rounded. The bed is up to one metre thick, and is thickest in the depressions on the surface of the agglomerate. It may be entirely eroded from the higher areas. All boulders are of volcanic origin, and the bed is considered to mark the onset of deposition following the erosion interval, which post-dates the (partial) deformation of the Lower Pouakai Agglomerate.

Upper Pouakai Sands: The sediments of this formation form the main part of the cliffs near New Plymouth. They consist mainly of coarse, loosely consolidated sands, which are in places hardened by limonitic solutions. Locally grit layers with occasional rounded pebbles are found, especially near the base of the sands. Components of boulder size are seen only on the flanks of the Lower Pouakai Agglomerate "highs". Most of the sand is volcanic in origin and well sorted. Occasionally, dark coloured bands rich in ferro-magnesian minerals alternate with light coloured bands in which feldspars and quartz grains are common. In general, the sediment is grey, but, due to its high iron content, it soon weathers to a yellowish-brown or brown colour. The sands can be up to 40 metres thick.

Cross-bedding is common. Although current bedding at the base indicates that the lower part of the Upper Pouakai Sands is very probably marine, the truncation angle of large-scale lenses in the upper portion of these sands shows that most lenses were deposited as dunes. Marine fossils are absent, and only rarely wood fragments were seen.

These sands may be correlated with the Rapanui Formation (Fleming, 1953) on the basis of morphological and lithological similarities, and may have been deposited during the last glacial stage, when lowering of the sea-level allowed extensive development of dunes.

Tuffs: The tuff beds form a disconformable veneer on the Upper Pouakai Sands. They are ochre-brown in colour, but pale brown when dry. Usually, they weather with numerous vertical cracks. The bulk of this sediment is fine volcanic dust, in which crystals of hornblende and feldspar and also small andesitic lapilli can be distinguished. Gibson and Morgan (1927) considered that the tuff is the product of a prolonged eruption of nearby Mt Egmont. The tuff beds are up to ten metres thick near New Plymouth.

Sugar Loaf Intrusives (Figs 1, 2, 3): The igneous rocks of the Sugar Loaves are light grey coloured and porphyritic in appearance. Large phenocrysts (up to 1 cm) of platy plagioclase feldspars are dominant. Together with both slender and more stubby needles of dark green hornblende, they are found in a groundmass of the same minerals.

In contrast with the Paritutu, Motu-e-Tamatea, and Ngataierua, the rocks of the Mataora-Pararaki twin islands are somewhat different. The feldspar crystals here are much smaller than in the other igneous masses; the rocks are less porphyritic and they contain more dark minerals. For a detailed petrological description, the reader is referred to Hutton (1944).

Geological History and Mode of Emplacement

For the present study, it was essential to find out whether the volcanic masses forming the Sugar Loaf Islands belong to one main intrusion or represent a system of individual intrusions. In this connection, it is assumed that the structural pattern of a macro-porphyritic rock reflects the internal movements of the magma before solidification. Most of the following information was obtained from the seaward sides of the Sugar Loaves, where exposures were fresh and free of talus.

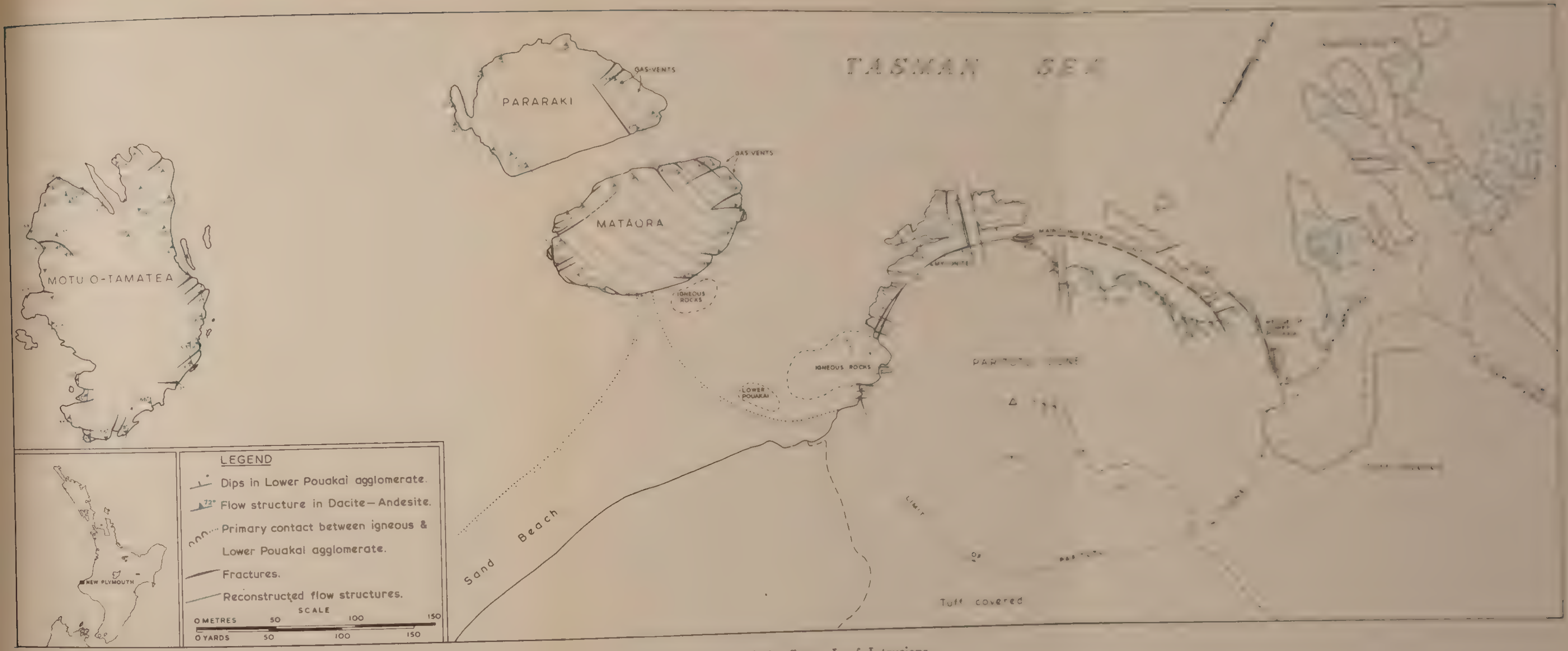

FIG. 1.—Geological map of the Sugar Loaf Intrusions.

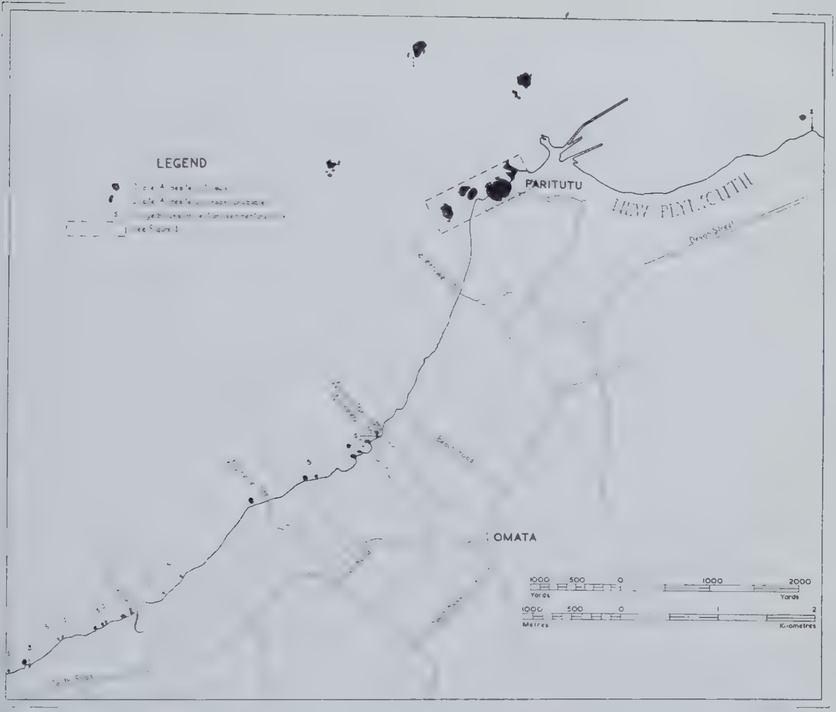

FIG. 2.—Sketch map of all volcanic intrusions in the New Plymouth area.

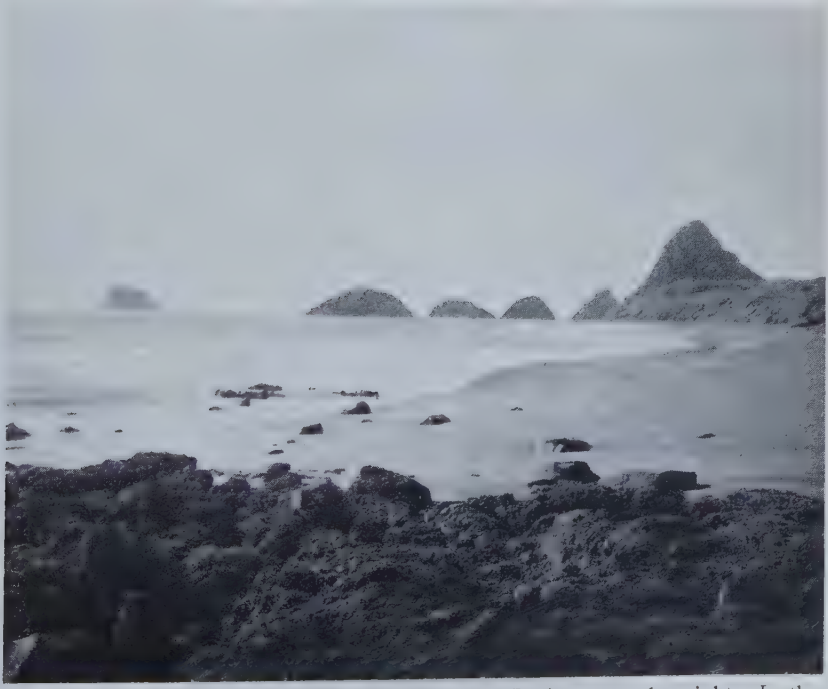

FIG. 3.—Sugar Loaf Islands from the south. Paritutu to the right. In the foreground the Lower Pouakai Conglomerate.

Three types of planar flow structures were seen on the steep flanks of the larger domes like Paritutu and Moto-e-Tamatea:

(1) A strong orientation of platy feldspar phenocrysts, and a less obvious but similar orientation of the more elongated hornblende crystals;

(2) A parallelism of ellipsoidal inclusions. These lie with their two longer axes parallel to the flow planes. Two main types of inclusions were recognized:

   (a) dark clusters of intimately intergrown hornblende crystals which may have been segregated in the magma;

   (b) light coloured inclusions which may be relics of incompletely absorbed country rock.

(3) A parallelism of jointing planes. Only the most persistent joint planes were recorded. They give an adequate picture of the internal structure, particularly of the larger Sugar Loaves. A jointing parallel to the flow planes was invariably observed. This type of jointing closely following the bending of the flow layers indicates a genetic relation with them. Another system of major joints in radial pattern with respect to the centre of a dome, and cutting perpendicularly through the flow planes, are regarded as tension joints, caused by the consolidation of the magma.

An interesting feature of the Paritutu dome is the presence of a major near-cylindrical zone of differential movement. It extends for about half the circumference of Paritutu on the seaward side. Most probably it is present, buried under the talus and tuff, on its landward side as well. This zone of movement is about 30 cm wide and is filled with finely ground rock-flour. Only differential movements in a completely solidified magma could produce such a pulverization of rock. This ring-fault also indicates that the core of Paritutu dome has been upthrust along a more or less vertical and cylindrical plane during the last stage of its growth.

During its rise, the igneous material forming Paritutu engulfed part of its wall rock, as an enclosed lens of sheared and slightly welded Lower Pouakai Agglomerate was found within the igneous rock at its north-eastern side. This lens, together with several other primary contacts between igneous and Lower Pouakai Agglomerate, gave useful indications concerning both the temperature of the uprising igneous rock and its date of emplacement. Since the contact phenomena are of a low grade, the temperature could not have been very high at the time of emplacement, which post-dates at least part of the deposition of the agglomerate.

Apart from the mylonite in the ring-fault, and the very mild contact phenomena, there are many more indications that the dacitic magma reached the surface in a very advanced state of cooling. Sharp bends in the flow layers are lacking (Fig. 4), and the rocks are very coarse textured. No lavas were formed and the Sugar Loaves did not con-

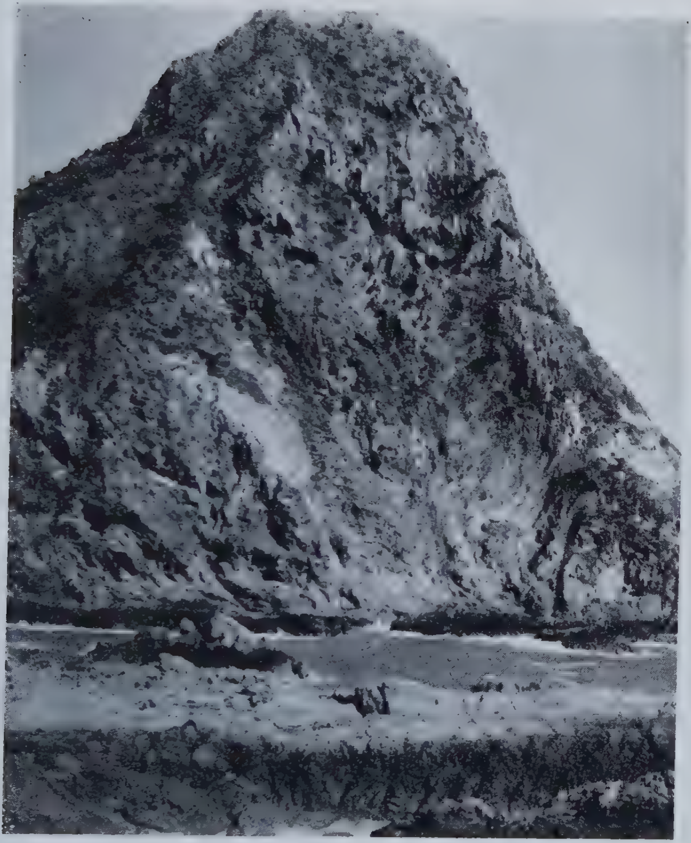

FIG. 4.—The Paritutu seawall showing flow structures.

tribute any recognizable rock-waste to the Lower Pouakai Formation in the neighbourhood. Rather, they formed prominent vertical structures without lateral flowing, and brecciated their own margins (e.g., at the base of the Paritutu on both the north-eastern and south-western sides).

At the back of the little bay to the east of Paritutu, the main part of the 25-metre high and steep cliff shows slightly stratified layers of partially waterworn boulders and finer volcanics. The layers, dipping away from Paritutu, gave the appearance of a talus apron from the plug dome. Closer inspection, however, revealed that the rock fragments vary greatly in colour, size, and texture and differ from the rather characteristic Paritutu dacite. The presence of mudstone pebbles within the pyroclastics, which elsewhere are found only in the Lower Pouakai, made it apparent that the cliff consisted of uplifted Lower Pouakai Agglomerate. Thus, as on the Omata Coast, a high-viscosity plug is invariably close to an agglomerate "high" and accounts for the latter's deformation.

The structure, as revealed by the arrangement of the flow planes (Fig. 5), shows that, in the case of Paritutu, the magma has actively pushed its way to the surface as an independent mass. The same applies to the dacitic mass of Motu-o-Tamatea. The structure of this island does not show completely closed marginal flow lines. The flow pattern on the south-west of Motu-o-Tamatea is complicated, and advanced erosion of the much jointed dacite makes interpretation more difficult. It seems, however, justified to regard this "Sugar Loaf" also as an individual intrusion with its centre probably somewhat to the south-west of its present top. Erosion has reduced parts of the rim.

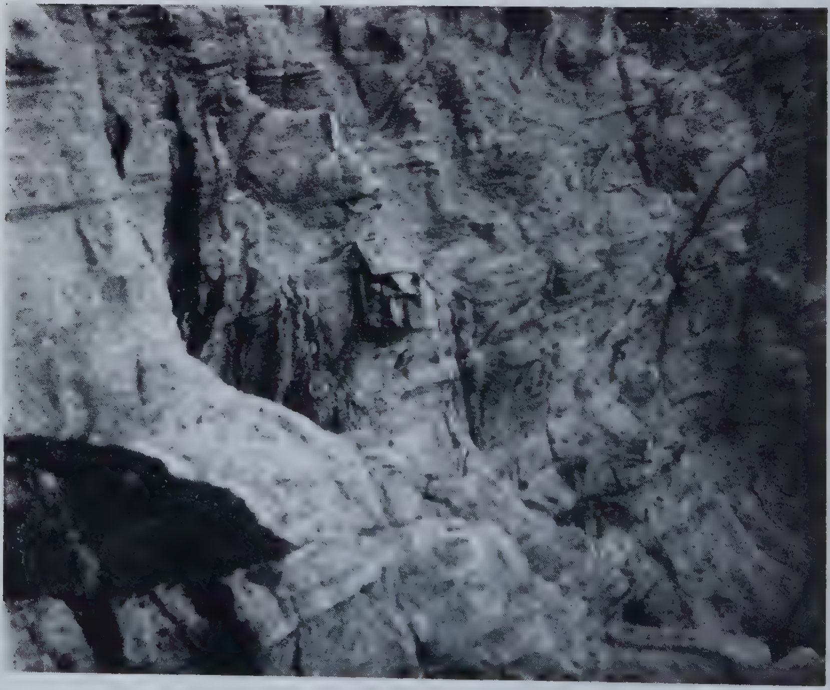

FIG. 5.—Detail of the foliation in the Paritutu seawall.

Flow lines continue across both the Mataora and Pararaki Islands, and, as the rock of both islands is similar, it appears that they represent one intrusion. It is unlikely, however, that the rocks of these islands should have been intruded simultaneously with the other Sugar Loaves, and it could well be that the Mataroa-Pararaki type, with its finer porphyritic texture and greater concentration of ferro-magnesian minerals, represents an earlier intrusion than the others. The Paritutu dacite, with its smaller amount of dark minerals, together with the greater size of the phenocrysts, could then have been a later intrusion, when settling and crystallization in the parent magma had proceeded further.

It appears that the field evidence is not compatible with one main intrusion nor with an injection of cone sheets as the mode of emplacement for the Sugar Loaves. The intrusions rose to the surface as individual masses, not necessarily all at the same time. They pierced through an existing cover of conglomerate, partly fracturing and dislocating it, and are thus best called protrusions. Both to the north-west and to the south-east of Paritutu, many minor plugs were found or their presence was inferred. The geographical distribution of the Sugar Loaves, and the related minor plugs, shows an elongation in a north-eastern direction. This is in accordance with recent unpublished gravity computations by E. Offner (pers. comm.), who furthermore concludes that the Sugar Loaves are only the minor and local surface expression of a large body of andesite, widening at depth. The emplacement of the Sugar Loaves, along nearly vertical injection paths, may be likened to the mechanism that produced the needle of Mount Pelee. Reports of comparable andesitic and viscous magmas, barely reaching the surface and, with their last effort, building a prominence without forming a crater are not lacking in geological literature. Those formed by almost a piston-like vertical upthrust compare well with the Sugar Loaves. Cotton (1952) mentions: Lassen Peak, California; the peaks on the island of Montserrat; the twin domes O-usu and Ko-usu, Usu volcano, Japan; and the Pitons of Carbet on the island Martinique. Further examples of very viscous lava are known in Taranaki—e.g., the more recent extrusions, forming German Hill, Brown Hill, the two "beehives" on the southern slope of Mount Egmont, and the Tholoid in the crater of the latter show the typical outline of craterless cumulo-domes. Apparently, semi-rigid lavas have been a common feature of Taranaki's volcanicity. Since more mobile lavas have flowed down Egmont's slopes also, the extrusion of semi-rigid lavas forming cumulo-domes (or in exceptional cases, like Paritutu itself, plug domes) may point to a late phase in the corresponding volcanic cycle.

Potentially, the dacitic magma forming the substructure was able to form cumulo-domes. It follows that the huge blocks of Tertiary mudstone, as well as the stratified blocks with pyroclastics, could have been brought upwards on the "carapace" of a rising nearly-solid igneous magma. It appears significant that the thickest development of the Lower Pouakai Agglomerate and the largest blocks (both sedimentary and fragmentary volcanic) within it are at the flank of the inferred large substructure of the Sugar Loaves. Thus, the distribution of the Lower Pouakai Agglomerate suggests that neither the Kaitake volcano nor the Pouakai volcano is the main source of the pyroclastics. It appears likely that the large stratified blocks with fragmentary volcanics have been derived from the talus banks of the substructures, on the top of which the Sugar Loaves are planted. These talus banks were fractured by later movements involving injection of highly viscous igneous rock. Sedimentary layers were affected also, and many blocks, some of huge size, were carried upwards. The uplifted blocks subsequently slumped down the sides of the growing substructure, which probably consisted of not one, but a great many cumulo-domes. This slumping is responsible for the chaotic position of all the stratified blocks in the Lower Pouakai Agglomerate. As Tertiary siltstones are known to be present underneath the Lower Pouakai Formation only at a depth of several hundred metres, the vertical movement of at least some of the blocks is not inconsiderable.

The intrusive activity, of which the protrusion of the Sugar Loaves proper marks the latest phase, is inferred to have caused the intense deformation of the Lower Pouakai Agglomerate. Most of the tilted blocks in the agglomerate were levelled by the erosion which preceded the deposition of the Upper Pouakai Sands. Some movements have, however, also taken place during the deposition of the Upper Pouakai, as evidenced by the way some Lower Pouakai "Highs" reach into the Upper Pouakai and furnished erosion products of boulder size into the Upper Pouakai Sands. It is likely, therefore, that the intrusive activity was recurrent, and did not cease before the end of the deposition of the Upper Pouakai beds.

CONCLUSIONS

The history of the igneous activity postulates the building of a large substructure on the summit of which the Sugar Loaves are found. Its genesis is intimately related to the depositional history of the Lower Pouakai Agglomerate, and early phases of igneous activity may have furnished much of the pyroclastic material in the agglomerate. Later recurrent phases are responsible for the intense deformation of the agglomerate, during which subaqueous slumping accompanied upthrusting movements of a very viscous magma.

The Sugar Loaf Islands proper are true craterless plug domes, produced by vertical piston-like protrusion of a nearly-solid dacitic magma. Their emplacement marks the latest phase of igneous activity, and is contemporaneous with both the erosion interval following the deposition of the Lower Pouakai Agglomerate and part of the deposition of the Upper Pouakai Sand.

ACKNOWLEDGEMENTS

The writer wishes to thank Shell B.P. and Todd Oil Services Ltd. and the N. V. de Bataafsche Petroleum Maatschappij (Royal Dutch/Shell Group) for the permission to publish this paper. Grateful acknowledgement is due also to Dr J. van der Sijp for his encouragement and active interest in the study. The author is indebted to Mrs L. Merz, who prepared the drawings for this paper.

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MAGNETIC SURVEY OF THE WAIRAKEI HYDROTHERMAL FIELD

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(Received for publication, 23 July 1959)

Summary

Drillholes penetrating below the hot aquifer at Wairakei have encountered diminishing temperatures, suggesting that the source of the hot water is not directly below the area now being exploited. A magnetic survey of the field indicates that hydrothermal alteration by which magnetite is converted to pyrite extends to the greatest depths in the western half of the field, that H_2S which is responsible for this conversion is therefore more abundant at depth in the west, and consequently this is the most likely feed source for the hot aquifer. The hot springs and drillholes draw on water percolating through the aquifer from this feed source.

INTRODUCTION

Magnetic surveys of some of New Zealand's hydrothermal fields have been discussed in a recent paper (Modriniak and Studt, 1959). Wairakei was shown to be an exception to the general rule that low magnetic intensities are measured around hot springs, and it was deduced that the springs and drillholes are fed by percolation of hot water beneath an impermeable cap from a source farther to the west. Since this may have a bearing on future exploration in this and other fields, it is necessary to examine closely the reasons for such a deduction.

The relevant portion of the Wairakei magnetic survey is reproduced in Fig. 1. This is a vertical force survey at ground level; contours are drawn at 50-gamma intervals relative to Wairakei absolute magnetic base (Cullington, 1954).

MAGNETIC INTERPRETATION

The general interpretation given in the earlier paper compared the high magnetic intensities in the east with the low intensities in the west, showing that the centre of the magnetic contrast causing this anomaly is about 3,000 ft below surface, and that the polarization contrast must be at least 500×10^{-6} c.g.s. units.

The polarization of core samples taken from the pumiceous tuffs and sediments in the upper 2,000 ft at Wairakei averages between 100 and 200×10^{-6} c.g.s., and these rocks cannot account for more than

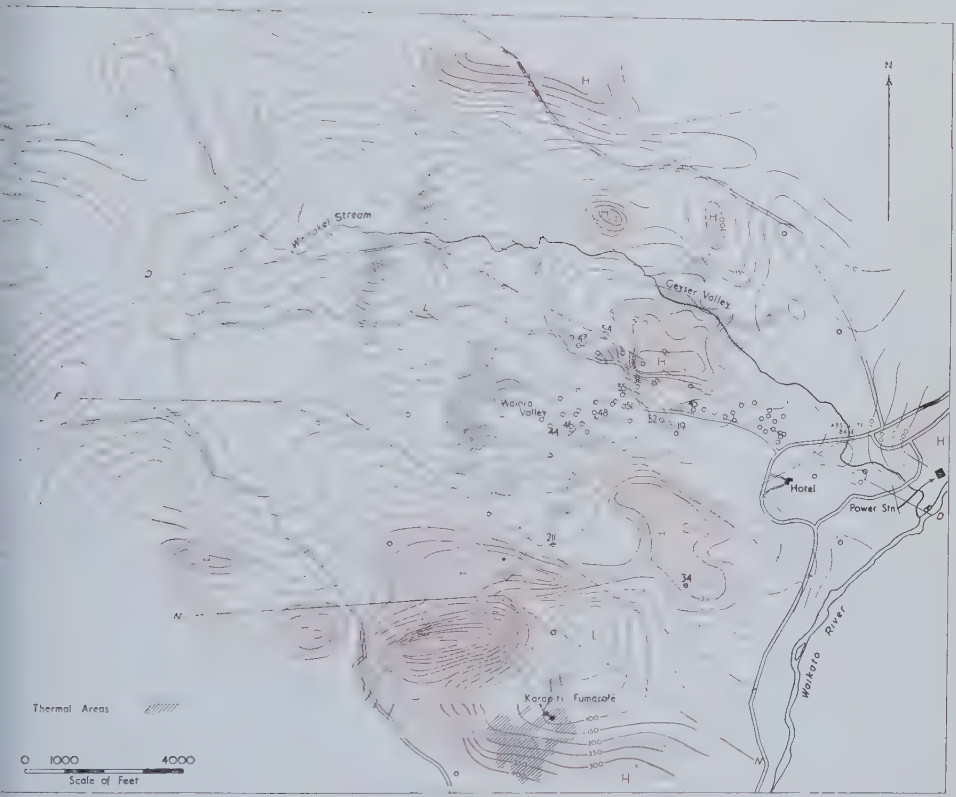

FIG. 1.—Wairakei vertical force magnetic survey at ground level. Contours at 50-gamma intervals relative to Wairakei absolute base (Cullington, 1954). Open circles indicate drillholes.

a fraction of the observed anomaly. The main cause is therefore deeper than 2,000 ft, and it has been identified with ignimbrite, more than 2,000 ft thick, found below this depth in the centre of the field. There are two possible explanations for the anomaly: either much or all of the ignimbrite is absent in the west, or the magnetic properties of the ignimbrite differ in the two sectors. There is no evidence for the first alternative, which is considered improbable. On the other hand, the magnetic polarization of an ignimbrite sheet usually shows little lateral variation, and the second alternative suggests an abnormal condition, such as hydrothermally altered rock in the west.

Wairakei drillholes penetrating ignimbrite have usually encountered decreasing temperature and hydrothermal alteration in this formation, and only one point has been located at which hot water appears to be fed into the Waiora aquifer from below; these findings strongly suggest that the main feed is not within the present production area at all. The implications of the magnetic survey may therefore be important, for, whether absence of ignimbrite or hydrothermal alteration is invoked to explain the low intensities in the west, either alternative is more consistent with hot-water feed from below than are the conditions so far found in the present production area.

Magnetic Properties of the Wairakei Ignimbrite

In order to further the interpretation, the magnetization of some ignimbrite core samples from Wairakei was examined; the author is indebted to Dr Trevor Hatherton for making these measurements. The results are presented in Figs 2 and 3, vertical polarization being plotted against depth from surface and temperature, respectively. The sum of remanent and induced polarization is plotted, but only the vertical component is considered, since the full orientation of the cores is not known; in all samples, the vertical remanence is known to be larger than the horizontal, and the vertical component of the earth's field at Wairakei is more than double the horizontal. The remanent and induced polarization are of similar order of magnitude, except where demagnetization is advanced and errors of measurement are correspond-

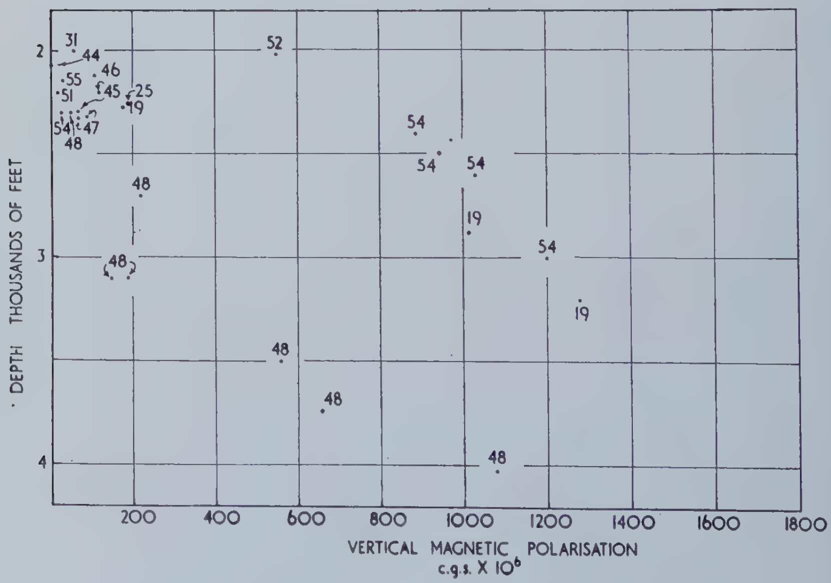

Fig. 2.—Wairakei ignimbrite core samples; plot of vertical magnetic polarization against depth from surface. Numbers indicate drillholes from which core was taken.

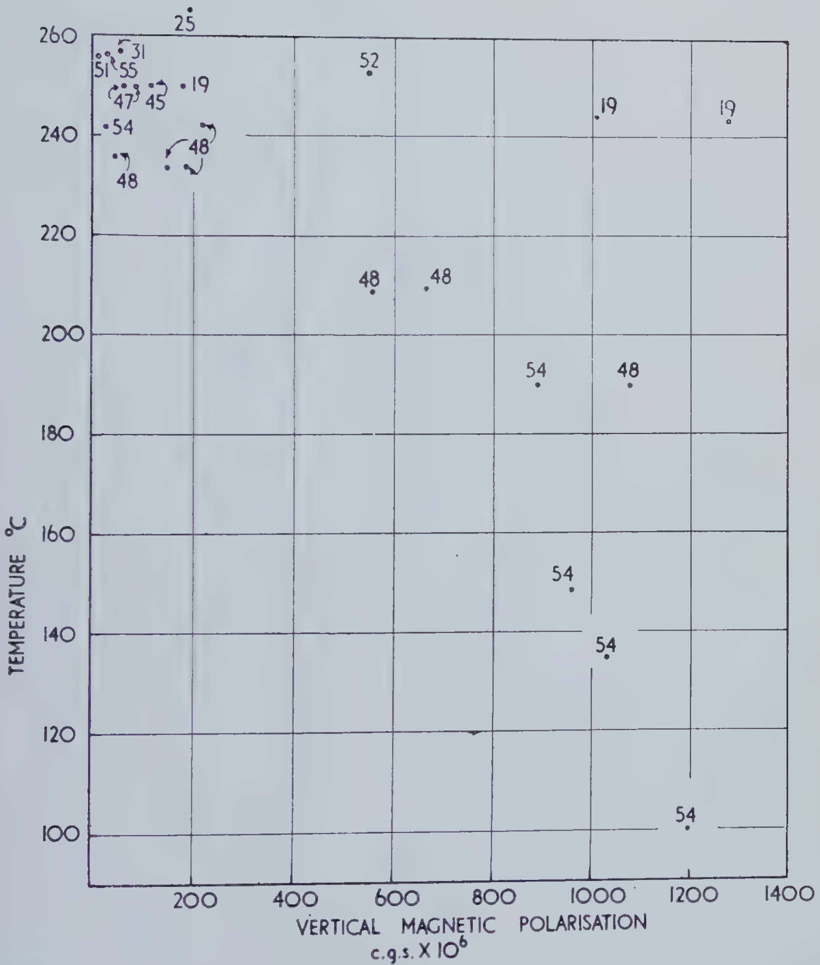

FIG. 3.—Wairakei ignimbrite core samples; plot of vertical magnetic polarization against temperature at the sampling point. Numbers indicate drillholes from which core was taken.

ingly high. The stability of the remanence at temperatures up to 260° C may be questioned, but, in his study of the Whakamaru ignimbrites, Hatherton has found only minor changes in remanence below 500° C (Hatherton, 1952).

Most Wairakei holes are drilled to produce steam, and few have been carried far below the optimum producing level, which is above the ignimbrite. Consequently, in the graphs, only three holes are represented which penetrated more than a few hundred feet into ignimbrite, and even in these holes discontinuous coring further limits the sampling range. However, Fig. 2 shows a correlation between magnetic polarization and depth, and Fig. 3 suggest that, except in holes 19 and 52, there may also be a correlation with temperature. The increase of polarization with depth is also consistent with decreasing hydrothermal alteration in the ignimbrite found by Mr A. Steiner (pers. comm.), but the reasons for such correlations must be examined before any attempt is made to extrapolate the findings into the western half of the field, where no cores are available.

Magnetite is present in the ignimbrite, and, since the magnetism of other constituents is small by comparison, only the magnetite need be considered. It is, however, known to be contaminated with titanium, either in solid solution or in crystal intergrowth; chemical analyses of ignimbrites published by Steiner (1958) show that the TiO_2 content is occasionally as high as 15% of the iron oxide content. Although the precise effect of this component is not known, it is unlikely to invalidate the arguments set out below.

Steiner (1953, 1955) has shown that hydrothermal alteration of magnetite yields pyrite (pyrrhotite is rare), while the titanium content gives rise to leucoxene and titanomorphite. These are the changes with which de-magnetization is associated at Wairakei, but they are found to take place over a wide range of depths and at temperatures ranging from 20° to 266° C, which appears at variance with the correlations shown in Figs 2 and 3. The conversion of magnetite to pyrite is a metasomatic process; that is to say, it depends on the introduction of sulphur from elsewhere. This sulphur is supplied in the form of hydrogen sulphide, carried in solution in the hot water, and the abundance of this component is a more likely controlling factor than either temperature or depth.

Foster (1959) has drawn phase diagrams for the system $Fe\text{-}FeS\text{-}FeS_2\text{-}Fe_2O_3\text{-}Fe_3O_4$ which have an important bearing on the interpretation of magnetic surveys in hydrothermal fields. These show that, for any given temperature and hydrogen content, and in the absence of a steam phase, a high H_2S content favours pyrite formation, while a low H_2S content favours magnetite. For any given H_2S and hydrogen contents, pyrite is stable at low temperatures and magnetite at high temperatures. Under the average gas concentrations measured in the Wairakei bores, the equilibrium temperature (i.e., that below which pyrite, and above which magnetite, is stable) is probably little higher than the maximum drillhole temperatures ($\sim 260°$ C). That it is higher is shown by the low magnetization of the rocks at these temperatures; therefore, pyrite is the stable mineral at all temperatures found in the aquifer. The hydrogen content may also influence the pyrite-magnetite equilibrium, but only to a limited extent; it cannot alone explain the low-temperature values in Fig. 3.

In the uppermost ignimbrite, conditions are similar to those in the aquifer above, and the rock is very weakly magnetized. Lower down, the magnetization increases, although the lower temperatures recorded here should favour pyrite formation. It must be inferred, therefore, that the H_2S content at these deeper levels is much lower than that in the aquifer. Of this, there is no direct evidence, but it is consistent with piezometric data, which show that at these levels cold recharge water flows in from the margins of the field (Studt, 1958).

In the vicinity of hole 19, conditions must be rather different, for, although the magnetization of the ignimbrite still increases with depth, the temperatures remain high and there can be little inflow of cold water. The poor output of hole 19, in spite of high temperature, indicates low permeability in this part of the ignimbrite, hence the movement of hot water must be slower here than elsewhere, permitting greater depletion of H_2S by reaction with the rocks before this hole is reached, and favouring the stability of magnetite.

EXTRAPOLATION WESTWARD

On the basis of the above arguments, it may be inferred that the weak magnetic intensities in the west imply the presence of H_2S-rich water at much greater depth in the ignimbrite than is the case in the present production area. Since the cold ground water does not as a rule carry enough H_2S, it may also be argued that hot water extends to greater depth in the west and that this is therefore a likely feed zone. No more precise deductions can be made regarding temperature.

The author has previously pointed out (Studt, 1958) that aquifer pressures in the western sector may not be adequate for steam production. The importance of the magnetic map lies in the suggestion that deeper holes might enter the ignimbrite in the neighbourhood of a feed channel, and that the hot water in this channel might be tapped at a significantly higher pressure than in the aquifer above.

It is worth noting that there are certain similarities between the magnetic data and the peizometric data prior to exploitation, so far as the latter are known. This is shown by a comparison of Fig. 1 with Fig. 4, showing 1955 aquifer pressures. Both maps show the contrast between the east and west parts of the field; high magnetic intensity is matched by low hydrostatic pressure, and vice versa. There is a salient of high pressure and low intensity extending eastwards through the middle of the field, and in each map there are steep gradients on the northern margin of this salient.

The piezometric surface is dependent on temperature distribution, or more precisely, since aquifer temperatures are known to be fairly uniform, on temperature distribution in the underlying ignimbrite. Correlation of Figs 1 and 4 therefore suggests that the distributions of temperature and H_2S in the ignimbrite are closely related, and further strengthens the argument for a westerly feed point.

The magnetic survey has indicated two other low-intensity salients to the north and south of that in which the producing drillholes are located. There is no surface evidence of hot water, but holes 211 and 34

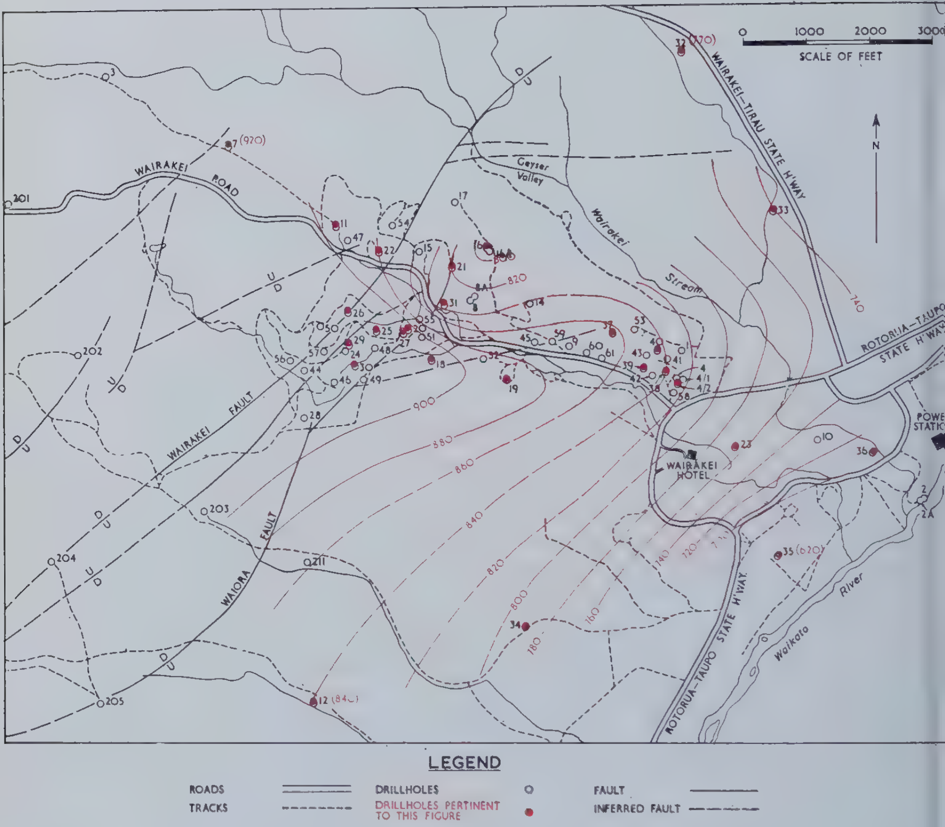

Fig. 4.—Piezometric surface, 1955. Contours at 20-foot intervals show the head, in feet of cold water, on a datum 500 ft above sea-level. (Reproduced from Studt, 1958.)

have proved that hot water is present at depth to the south. It is considered that these two salients probably mark eastward percolation of hot water from a source in the west, just as in the drilled sector. In the south, however, the holes have also shown that rhyolite cuts into the Waiora aquifer and, since this introduces new conditions, both magnetic and hydraulic, extrapolation in this direction must be treated with caution.

The Time Factor

The time factor has been completely ignored in the above arguments. The initial alteration of magnetite may be rapid, but, even assuming that dynamic conditions maintain a high concentration of hydrogen sulphide, the alteration will become progressively slower as it depends more and more on diffusion through less permeable sections of the rock. The retention of some magnetic polarization in highly altered regions is therefore understandable and does not constitute evidence for recent inception of the alteration.

Foster's phase diagrams show that co-existence of pyrite and magnetite should be rare, except in a transient state, and the fact that Fig. 2 shows a transition rather than a sharp contrast in magnetic properties suggests that equilibrium conditions do not exist in the ignimbrite. But without some suggestion of the time scale involved, it would not be valid to speculate whether the present conditions have existed *ab initio*, or are due to relatively short-term oscillations in the controlling factors.

Especially is this true when the reverse reaction is considered—that is, conversion of pyrite back to magnetite. At high temperature, this may proceed rapidly, but the persistence of pyrite ore-bodies and pyritized sediments suggests that at low temperatures this reaction seldom becomes important, possibly because the H_2S concentration seldom falls low enough. Were it not for correlation with hydrothermal data, alteration of ignimbrite in the west at Wairakei might be merely a relic of past activity, and the H_2S concentration might be no more than that required for stability of pyrite at normal ground temperatures.

Exploratory holes are shortly to be drilled by the Ministry of Works crews at Wairakei to examine the conditions in the west and test the interpretation discussed above. This may not succeed in proving any large addition to the exploitable resources, but, by widening the scope of hydrological and other data, it will certainly aid the efficient exploitation of the field.

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The author wishes to acknowledge his indebtedness to the following officers of the Department of Scientific and Industrial Research: Dr T. Hatherton, for magnetic measurements on core samples; Dr P. K. Foster, for clarification of chemical aspects; Mr A. Steiner, for petrological information. Core samples were supplied by the Project Engineer, Ministry of Works.

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HOKONUI STRATIGRAPHY OF THE AWAKINO-MAHOENUI AREA, SOUTH-WEST AUCKLAND

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(Received for publication, 13 February 1959)

Summary

Trias-Jura rocks of the Awakino-Mahoenui area constitute part of the western limb of the Kawhia Syncline in its southern-most exposure. The syncline is approximately meridional in alignment and pitches northwards at a low angle. Strata have dips varying from nearly vertical in the west of the area to about 15° east at the top of the succession in the east. The strata form the Herangi Range which originated as a north-south fold of the peneplained surface resulting from the post-Hokonui orogeny. This fold is believed to be faulted on its western edge, but while this is also the case on the eastern limb farther north, in the Awakino-Mahoenui area faulting seems not to have occurred at the surface.

The oldest beds exposed are 7,000 ft of Oretian (lower Carnian) which are believed to be the equivalent of 2,100 ft of strata above the Moeatoa conglomerate at Marakopa. These are followed conformably by 2,200 ft of Otamitan strata (Carnian), 1,800 ft to 2,300 ft of Warepan (Norian), 2,800 ft of Otapirian (Rhaetian), 2,500 ft of Aratauran (Hettangian-Sinemurian), about 2,000 ft of Ururoan (Pliensbachian-Toarcian), about 4,000 ft of Temaikan (Bajocian-Oxfordian), and 4,300 ft of Heterian (Kimeridgian), giving a total of 14,000 ft of Triassic and 12,000 ft of Jurassic strata. Beds of Heterian age make up a greater thickness than in other North Island localities. On the south shore of Kawhia Harbour there are some 500 ft of beds, including Temaikan, between the type Temaikan and the black, gritty sandstone of Totara Peninsula, whereas below the Palmer Creek Shellbed (the same horizon as the black sandstone) there are 3,500 ft of Heterian strata.

The sediments are mainly bedded sandstones and siltstones, with scattered and widespread tuffaceous material. True conglomerates are rare and thin, but grits are more common. Carbonaceous beds occur in the Otapirian and Heterian and accompany thin coals in the Oretian, but no non-marine beds typical of the type Temaikan sequence were observed in strata of Temaikan age. Calcareous beds are found at various levels in the Jurassic sequence but only Aratauran strata were found to contain microfossils.

Marine fossils are widespread and allow closer subdivision of some stages. Warepan beds contain numerous forms of *Monotis* whose stratigraphic distribution enables four subdivisions to be recognized in the area. *M. richmondiana* is found in the older beds; *M. calvata* is confined to the upper Warepan; while middle Warepan strata contain a very varied fauna including forms recognized by Trechmann (1918) and others recorded from New Caledonia (Avias, 1953). The Otapirian Stage is divided after Campbell (1956) although his basal fauna was not recognized in the area. Ururoan beds are divided into those containing *Pseudaucella* (Pliensbachian) and those with *Dactylioceras* (Toarcian). This ammonite was not found, but the fauna enables ready correlation with the beds containing it at Ururoa Point.

INTRODUCTION

The area studied in this survey (Fig. 1) covers approximately 53 square miles. The purpose of the investigation was to apply to this area, geologically untouched for over 30 years, the recently erected stratigraphic divisions of the Hokonui System (Triassic-Jurassic) in order to allow closer correlation with areas elsewhere in New Zealand. Field

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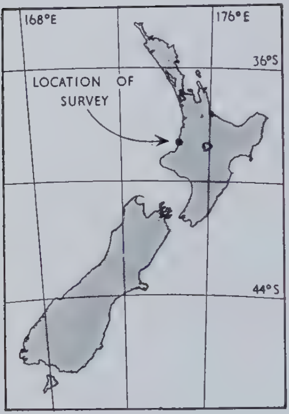

Fig. 1.—Locality map.

work was carried out as part of the requirements for the Master of Science degree during the period October 1955 to February 1957. Field maps were prepared from the New Zealand Mapping Service Series 4 (1:25,000) aerial mosaics of Sheet N91 (Mokau), but in 1957 the inch to the mile map was published and this has been used as the basis for the accompanying map (Fig. 2).

In mapping, special emphasis was placed on tracing the Mesozoic and Tertiary contact, either by direct observation or by inference from the change of slope, Hokonui beds being able to maintain steeper valley slopes than can the Tertiary strata, with the exception of the Te Kuiti Formation. As a result this boundary can be shown in greater detail than was possible on the earlier map (Henderson and Ongley, 1923).

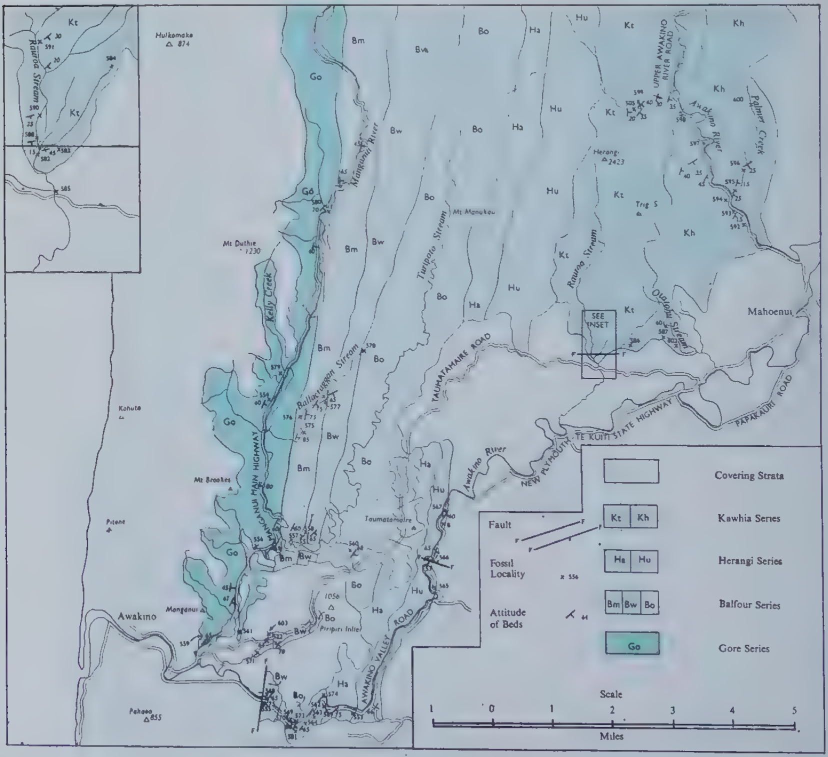

Fig. 2.—Geological map of Mesozoic rocks of the Awakino-Mahoenui area.

PREVIOUS WORK

Little previous work has been done specifically on the Mesozoic rocks of the area studied. This was due, in the early days of the Geological Survey, to the inaccessibility of the area because of lack of communications, the heavy bush cover coupled with the very rugged topography, as well as to the hostility, from 1859 until 1878, of the local Maori people. Until the reconnaissance survey commenced by Henderson and Ongley (1923) in 1917, the early literature of the geology of Taranaki and the King Country is almost exclusively concerned with the search for coal and oil.

The first geologist to visit the Awakino Valley was Park (1887) who travelled to its mouth from beyond the northern limit of the district. He examined Mesozoic pebbles in the bed of the river but could not locate the rocks *in situ* in the upper part of the valley. He recorded the rocks as argillaceous sandstones and shales and, "at a point about fifteen miles from the mouth of the river, in the bed of a small stream flowing from the north", he found fossils which "indicate a Secondary age for these rocks" (Park, 1887, p. 177). These fossils probably came from Ururoan beds on Awakino Valley Road.

During much the same period, Cussen (1887) was engaged in the triangulation of the King Country and he briefly described the physiography and geology. He correlated the same rocks with the Maitai slates and placed them in the Carboniferous.

In a preliminary report after the reconnaissance survey mentioned above, Henderson (1919) briefly noted the synclinal structure of the Mesozoic beds, which he estimated range in age from Triassic to upper Cretaceous. However, in the final report, Henderson and Ongley (1923) modified this, stating that the beds range from Triassic to upper Jurassic or perhaps lower Cretaceous. Their report was used as the basis for the present work and the writer's conclusions are in substantial agreement with those of these authors, though there is reason to believe they have rather too readily invoked faulting to explain structure and stratigraphic relationships.

STRATIGRAPHY

GENERAL

In the Awakino-Mahoenui area, the exposed basement consists entirely of Hokonui rocks ranging in age from upper Triassic (Oretian) to upper Jurassic (Heterian). These rocks form the basement everywhere in the district, but only the central strip, the Herangi Range, is generally free of covering strata. This strip is bounded to the south and east by the Awakino River, to the north-east by its tributary, Palmer Creek, and to the west, covering strata are absent up to half a mile west of Manganui River. (This latter and Awakino River are the two major rivers of the area and, over most of their length, flow meridionally along the strike of the Hokonui strata—see map, Fig. *2*). To the south-west the strip is covered by thin Tertiary deposits of Taumatamaire Hill, except for a small area occurring as an inlier in the valley of the middle reaches of Piripiri Stream, here named the Piripiri Inlier.

South of Awakino River the Hokonui rocks are covered by Tertiary deposits which increase in thickness southwards to the south Taranaki coast. At Uruti, about 20 miles south of Awakino, they were found in a borehole nearly 1,000 ft below sea-level and contain (?lower) Jurassic Foraminifera (Hornibrook, 1953). Northwards the beds continuously outcrop to Kawhia Harbour.

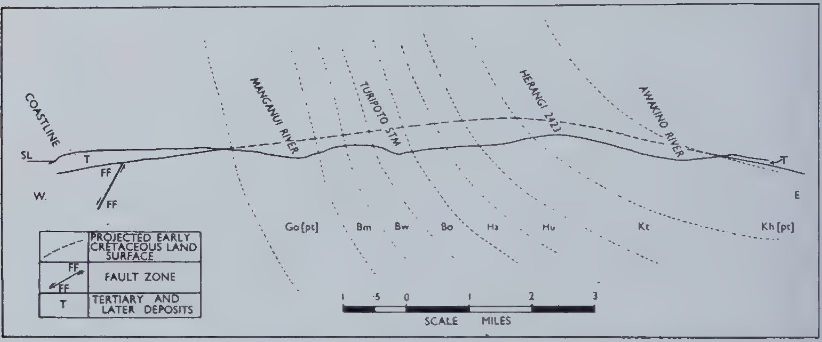

Fig. 3.—East-west cross-section in northern part of Awakino-Mahoenui area.

Beds of the Hokonui System in the area form part of the western limb of the Kawhia Syncline (Fig. 3) which strikes north-south and pitches north at a low angle. Sediments were deposited in relatively shallow water off the eastern edge of what was probably a continental massif. The area then was part of the New Zealand Geosyncline which had probably been initiated in the Devonian (Wellman, 1956, p. 24) and which formed the southern extension of the Papuan Geosyncline. In the sediments of the New Zealand Geosyncline two facies can be recognized, a deeper-water Alpine facies and a shallower-water Hokonui facies, the latter deposited in the marginal syncline bordering the ancient land (Wellman, 1952). Sedimentation in the marginal syncline in general kept pace with sinking of the ocean floor, but at times was more rapid, and terrestrial or estuarine beds were deposited. The Triassic sediments have been regarded as entirely marine, but a period of non-marine deposition is shown by the presence of thin coals in the Manganui Valley. In the mid-Jurassic, terrestrial conditions are shown elsewhere by the fossil forests of Waikawa and Te Maika, but perhaps owing to the unfavourable nature of the terrain this regression of sea-level has not been proven in the Awakino-Mahoenui area.

Apart from the non-marine beds, Hokonui sediments in the area are of the Flysch facies. Generalized comments on changes of lithology throughout the Hokonui facies (Wellman, 1952) are applicable to the area under review. The Jurassic beds, for instance, contain calcareous material, glauconitic bands, and bands of spheroidally-weathering sandstones, not encountered in the Triassic deposits. On the other hand, plant fragments are more common in the Triassic. Tuffaceous material is common at many horizons and nodules or crystals of pyrite have been noted in both Triassic and Jurassic beds. Although Jurassic deposits are usually somewhat coarser than the Triassic, conglomerates are uncommon, thin, relatively fine, and generally of the sharpstone type. While the terms greywacke and argillite are generally applied in New Zealand to rocks of the Hokonui and Alpine facies, true greywackes seem to be rarely found, the main rock-types represented in this area being bedded sandstones and siltstones. (Fig. 4).

In all, the exposed Hokonui sediments have a maximum thickness of approximately 26,000 ft, of which about 14,000 ft are of Triassic age. This thickness is comparable with that of 28,200 ft estimated by Williamson (1932) for the same beds in the Te Kuiti Subdivision, and of 28,000 ft given by Henderson and Grange (1926, p. 31) for the Huntly-Kawhia area.

After the close of the Hokonui period of sedimentation and during the post-Hokonui orogeny, the Kawhia Syncline was formed, and the beds were affected by meridional faults and folds. Henderson and Ongley (1923) explain the Herangi Range as a fault block, while MacPherson (1946) regarded it as part of the earliest secondary fold of the North Island multiple arc. Although several strike faults were observed, the writer considers that the eastern flank of the range is fold-, and not fault-controlled. The western edge, however, is more likely to be the result of faulting, probably that which causes Jurassic beds to be exposed at Albatross Point, Kawhia South Head (Mason, 1952) and which Hornibrook (1953) postulated as extending as far south as Uruti, north Taranaki. In the Te Kuiti Subdivision the eastern flank was shown by Marwick (1946) to be fault-controlled in the northern part, but "south of this . . . the section across Maungamaungero does not indicate faulting" (Marwick, 1946, p. 13), and this condition evidently prevails southwards into the area under review.

The Mesozoic rocks are locally affected by small strike faults and two faults transverse to the fold were also observed, but all are unimportant.

Early in the Tertiary sea-level rose and since then has fluctuated considerably, depositing marine Tertiary beds with some coal seams and Quaternary beach, estuarine, and fluviatile deposits. They overlie the Mesozoic rocks with marked unconformity and dip away from the Herangi Range on the west, south, and east flanks. This suggests that the range remained as a high, perhaps sometimes above sea-level, or that the fold continued to grow during most of Tertiary times.

DETAILED MESOZOIC STRATIGRAPHY

The historical basis for series and stage names has been adequately treated by Marwick (1953), Campbell (1955), and Campbell and McKellar (1956), and will not be discussed in this paper.

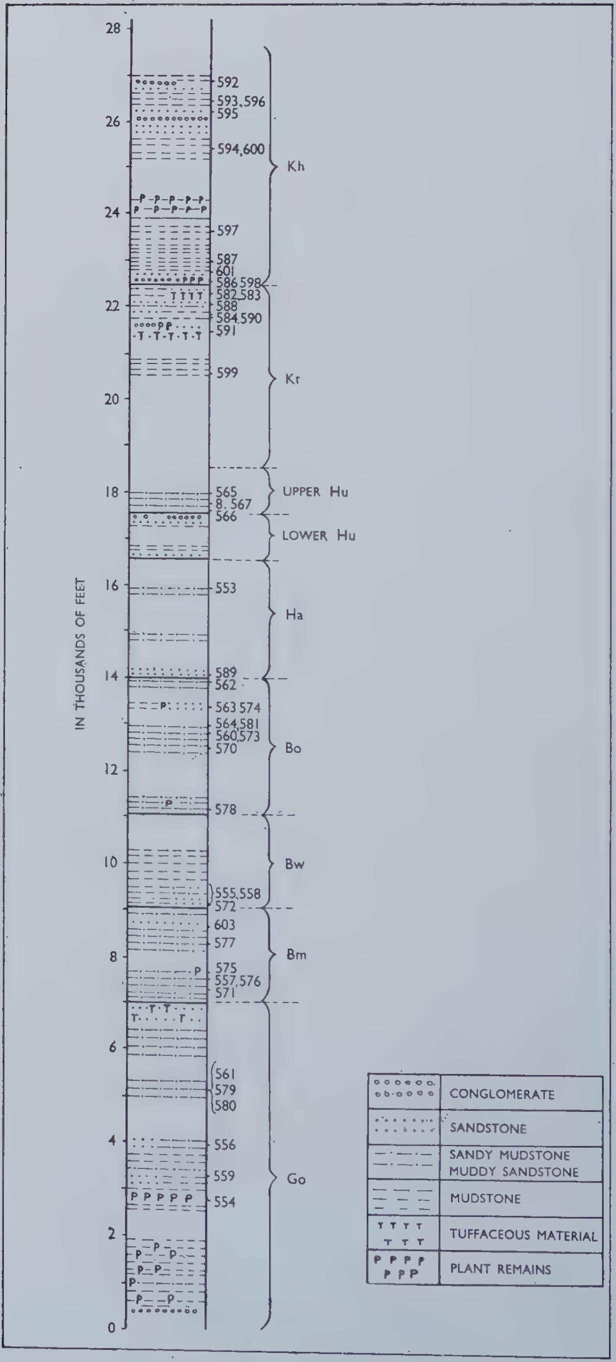

FIG. 4.—Generalized stratigraphic column of Awakino-Mahoenui Hokonui beds.

Gore Series

ORETIAN STAGE

Rocks correlated with the Oretian Stage (lower Carnian) of the Gore Series crop out as a strip on the western edge of the Herangi Range, generally west of the Manganui River, though in its lower part the river flows 25 to 30 chains west of the upper boundary of the stage. To the west and south these rocks are covered by Tertiary sediments. In the valley of an east-flowing tributary of Manganui River west of N91/554, the estimated thickness of rocks exposed is 7,000 ft, which, because of the great variation in dip and strike of strata involved, could be in error by 500 ft. Farther north, in the Marakopa district, Williamson (1932) recorded 2,500 ft of strata which on stratigraphic position and lithology he correlated with the Oreti "Series" of Southland. Campbell (1955) has estimated the thickness as about 2,100 ft and has shown that the underlying 4,000 ft-thick Moeatoa "Series" (Williamson, 1932) is also Oretian. The total of 6,000 ft approximates to that of strata in the Manganui Valley, but it is unlikely that this approximation gives a true picture. Firstly, the Moeatoa beds consist of thick igneous conglomerate with lenses of sandstone, siltstone, and tuff, quite unlike any seen by the writer in the Manganui Valley, although the possibility of lateral facies variation cannot be ruled out. Secondly, on the regional strike, Moeatoa beds would pass beneath the Tertiary cover west of Manganui Valley, and no major east-west faults are known to complicate the structure. It seems, therefore, that the 7,000 ft of Oretian in Manganui Valley is the equivalent of all or most of the 2,100 ft at Marakopa.

The average dip over the area is about 70° east varying from vertical at a quarry on Manganui Road (N91/556) to 45° east in a dip-slope bluff near the road some 50 chains farther south. The general trend of the rocks is about 010° but the strike swings between 345° and 025°.

The rocks are much more shattered, sheared, and compacted than any others in the district, and these three characters increase sharply westwards from the lowermost *Mytilus* beds, indicating proximity to a zone of strong faulting and crumpling. This zone probably lies to the west of the exposed Triassic rocks and may approximately follow the strike, thus influencing the position of the coast-line in the area and north to Tirua Point. The presence of such a zone would account for the variation in attitude of the rocks in the western section of Mesozoic beds .

These older beds are coarser than the younger, with sandstones and grits more common. Conglomerates were seen at two lcoalities, but there are no beds similar to the thick conglomerates farther north in the Marakopa area. Bands of pink and white material, probably tuffaceous, are especially common in sandstones at the top of the stage, and unidentifiable plant fragments are abundant in siltstones and shales in the lower part. Fragments of wood are also common in the lower part, and in a black mudstone in the valley west of N91/554 they are found with nests of small pyrite crystals and thin veins of opal.

In the upper part of the sequence fossils occur at a few localities, usually in relatively large numbers. Due to the post-consolidational movements they are almost invariably somewhat distorted.

The lowest beds in the district with identifiable remains crop out on Manganui Road about 1½ miles by road south of Kelly Creek (N91/554*). Here estuarine or fresh-water white, buff, and brown clays contain much plant debris, including a 2 to 4 in. coal layer. Henderson and Ongley (1923, pp. 23-4) recorded impressions of eight species of plants but the locality is now so deeply weathered that only specifically unidentifiable *Cladophlebis* and *Taeniopteris* were collected. These authors correlated the beds with similar ones overlying *Monotis* beds in the headwaters of Ballacraggan Creek and regarded both as of Rhaetian age. A sample of the thin coals associated with the plant remains was submitted to Dr R. A. Couper, New Zealand Geological Survey, Lower Hutt, who reported (pers. comm.) that "the preparation is dominated by winged pollen grains of pteridospermous and coniferous origin. The absence of characteristic Jurassic forms suggests a Triassic or older age . . . but I cannot put a lower age limit on the sample". Regarding the suggestion of Rhaetian age, Dr Couper stated that "overseas Rhaetic macrofloras certainly have a 'Jurassic aspect' and I would have expected a few Jurassic forms in a Rhaetic microflora".

The oldest beds in which molluscan remains were observed crop out for 5 chains along Manganui Road ¼ mile north from its junction with Taumatamaire Road (N91/559) and lie about 2,250 ft below the top of the stage. The beds at the base of the succession here strike 025° and dip 75° east, but the attitude towards the top imperceptibly changes, the beds striking 010° and dipping 55° to 65° east. The fauna of these beds includes, as well as an unidentified genus of the Pteriidae, the following fossils:

"Rhynchonella" 3 spp.
Athyris sp.
"Terebratula" sp.
Palaeoneilo 2 spp.
Pseudolimea 2 spp.
Anodontophora angulata Trechmann
Anodontophora sp.
?*Raphistomella* sp.
Amberleya sp.

The standstones and siltstones in a quarry on Manganui Road nearly 2 miles north of the above sampling area are of about the same horizon or slightly younger and from them (N91/556) were collected:

"Rhynchonella" aff. *zealandica* Trechmann
Athyris wreyi (Suess)
Pseudolimea sp.
Pleurotomaria aff. *hokonuiensis* Trechmann

Henderson and Ongley (1923, p. 23) recorded the following fossils from the same locality:

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*Such numbers are for fossil collections from within the boundaries of sheet N91 recorded in the New Zealand Regional Fossil Record System.

Dielasma sp.
Terebratula sp.
Athyris wreyi (Suess)
Isocrinus trechmanni Bather
?*Cucullaea wellmani* Marwick*
Halobia cf. *austriaca* Mojsisovics
Anodontophora edmondiiformis Trechmann
Pleurotomaria sp.

The three outcrops mentioned below have beds which are some 1,400 ft higher in the succession than those previously mentioned.

In hard, dark grey, indurated siltstone on the north bank of a small creek flowing westwards into Manganui River (N91/561), the following fossils were identified:

"*Rhynchonella*" sp. A
"*Terebratula*" sp. A
Isocrinus n.sp.
Halobia hochstetteri Mojsisovics
Limatula sp. A

Hard grey argillaceous sandstones in a bluff on Manganui Road about 16 chains south of the mouth of Kelly Creek yielded the following forms (N91/579):

"*Rhynchonella*" sp.
Spiriferina (*Psioidea*) *australis* Trechmann
Dielasma cf. *himalayana* Bittner
Halobia lilliei Marwick
Limatula sp. A
?*Tancredia* sp.

At a quarry some 3 miles farther north along the road numerous fossils occur in various bands in shattered grey argillaceous sandstones (N91/580). The fauna includes:

Monotrypella maorica Wilckens
"*Rhynchonella*" sp. A
Dielasma cf. *himalayana* Bittner
Dielasma n.sp.
"*Terebratula*" sp. A
Isocrinus n.sp.
Myophoria sp.
Halobia lilliei Marwick
Lima sp.
Limatula sp. A

Above these beds are about 850 ft of apparently unfossiliferous beds which, with tuffaceous sandstones and arenaceous mudstones at the top, pass conformably into beds of Otamitan age.

The beds discussed above contain none of the forms that Campbell (1955) has noted as being restricted to Oretian beds, except *Cucullaea wellmani*. *Monotrypella maorica* occurs in both Kaihikuan and Oretian

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*Marwick (1953, p. 51), in describing *C. wellmani*, did not record it as occurring at this quarry, though he identified *Macrodon* cf. *curionii* Bittner, which he placed as a synonym of his species, from this locality (Henderson and Ongley, 1923, p. 23).

beds, *Dielasma* cf. *himalayana* ranges from Kaihikuan to Otamitan, and *Spiriferina (Psioidea) australis, Athyris wreyi,* and *Halobia* are found in Oretian and Otamitan rocks. The presence of *Halobia* precludes the possibilities of these beds being Kaihikuan, while the absence of *Mytilus problematicus* from the basal 7,000 ft of Triassic rocks exposed suggests an age older than Otamitan, and therefore the beds considered here are correlated with those at the type locality of the Oretian Stage.

Balfour Series

OTAMITAN STAGE

In the Awakino-Mahoenui area rocks of the Otamitan Stage (Carnian) crop out in a strip immediately east of the Manganui River in the south and in the Manganui gorge in the north. In the Turipoto Stream area, this strip is about 30 chains wide while its width in the northern part of the district is about 40 chains. After passing beneath the Tertiary sediments of Taumatamaire Hill beds of this age reappear in the south-west end of the Piripiri inlier, cropping out for nearly 20 chains in Piripiri Stream and on Taumatamaire Road. Farther south they are again covered by Tertiary ferruginous sandstones of the Mokau Formation.

The regional strike of the rocks is about north-south, varying locally from 350° to 015°, and dips range between 45° and 85° east, the average dip being about 75° east. Rocks comprising the stage maintain the same thickness of some 2,200 ft from Ballacraggan Creek northwards but thin in the southern part, being about 1,450 ft thick in the Turipoto Stream area. It is quite apparent that the thickness of the beds varies considerably in different regions. Marwick (1946, p. 25) recorded 700 ft of Otamitan beds in the Te Kuiti Subdivision. Henderson and Ongley (1923, p. 22) stated that the *Mytilus* beds are separated from the *Monotis* beds by 800 ft of unfossiliferous sediments, and that the *Monotis* "zone" lies "1,000 ft above and about 20 chains east of the *Mytilus* zone" (p. 19). Reconnaissance by the writer, however, has shown that the thickness of rock between the base of the *Mytilus* beds and the base of the *Monotis* beds is everywhere greater than 1,000 ft and up to twice that amount. The apparent discrepancy in figures is probably due to the extension of the lower limit of the occurrence of *Mytilus problematicus*, key fossil for the stage, during the present survey and also to a closer examination of the rocks than was possible in the earlier reconnaissance.

Rocks of the Otamitan Stage consist almost entirely of hard, grey, arenaceous siltstones, both bedded and massive, though near the top of the sequence very weathered, coarse sandstone and grit are exposed on Taumatamaire Road (N91/603). These beds, with the exception of the sandstone and grit, differ markedly in lithology from those at the type locality which Trechmann (1918, p. 178) described as well-bedded feldspathic sandstones, argillites and shales.

Fossils occur plentifully in the lower 1,000 ft of the stage, sometimes crowded into shell-beds, but are rare in the upper part. The fauna throughout is a uniform one and there seems little possibility of subdividing the stage.

The basal beds of the stage, overlying weathered Oretian tuffaceous sandstones, are exposed on Manganui Road in the extreme north of the area covered, and consist of sandy and slightly tuffaceous mudstones with *Mytilus problematicus* Zittel, *M. mirabilis* Trechmann, and an unidentified pelecypod. The beds strike 350° and dip eastwards at 45°.

In Piripiri Stream the following fossils were found (N91/571) about 1,400 ft below *Monotis* beds:

Athyris wreyi (Suess)
Halobia hochstetteri Mojsisovics
Mytilus problematicus Zittel
Anodontophora ovalis Trechmann

Ballacraggan Creek, over most of its middle and lower course, runs along the strike of the beds and many localities of about the same horizon can be examined. They have yielded the following fauna, associated with fragments of a coniferous wood (N91/575, 576):

"*Palaeoneilo*" sp.
Halobia hochstetteri Mojsisovics
?*Hokonuia limaeformis* Trechmann (juvenile)
Mytilus problematicus Zittel
M. mirabilis Trechmann
Anodontophora ovalis Trechmann

The highest fossiliferous Otamitan horizon located in Ballacraggan Creek is at the base of a 15-ft waterfall some 560 ft below the *Monotis* beds. Here (N91/577) were found *Halobia hochstetteri* Mojsisovics and an unidentified, flat, almost involute, only slightly asymmetrical gastropod showing affinities with Trechmann's *Atlantobellerophon*, though no evidence was seen of a selenizone.

In the region between Ballacraggan Creek and Piripiri Stream numerous fossils were found at the junction of Turipoto Stream with Manganui River and for 20 chains upstream in the latter (N91/557). The following were collected here:

Spiriferina cf. *otamitensis* Trechmann
"*Terebratula*" sp.
Halobia hochstetteri Mojsisovics
Hokonuia limaeformis Trechmann
Mytilus problematicus Zittel

The youngest fossiliferous Otamitan beds located in the area are the previously mentioned weathered sandstone and grit on Taumatamaire Road (N91/603), in which were found several specimens of *Athyris wreyi* (Suess), some 300 ft below *Monotis* beds.

WAREPAN STAGE

Monotis richmondiana Zittel has long been regarded as the key fossil for the Warepan Stage (Norian) and has often been used to cover all specimens of the genus found in New Zealand, although Trechmann

(1918) had early recognized ten different forms. Marwick (1946, p. 28) noted that a number of varieties were found in the Marakopa area, and (1953, p. 58) described the new species *M. calvata*. Similarly in New Caledonia *richmondiana* had been used for all specimens of the genus until Avias (1953) recorded others as well. Likewise in the Awakino-Mahoenui area, detailed collecting has shown the presence of species and subspecies other than *richmondiana*, many of which are potentially useful for the closer subdivision of the stage.

As will be seen, a number of different forms are commonly found in the same bed and this poses a problem in paleoecology. It is considered unlikely that they lived together in the same environment but the alternative of current accumulation of dead shells also seems unlikely, since there is no sign of breakage of these apparently fragile and thin shells. Wellman, Grindley, and Munden (1952, p. 225) thought it likely that the shell-beds had been concentrated from less abundantly fossiliferous material, the finer sediment being removed, and this would certainly lead to thanatocoenoses. Transportation seems disproven in cases where the majority of shells remain articulated, since the pteriid hinge can not have been very strong. Decay of the ligament and subsequent wave or current action would readily allow separation of the flat right and arched left valves. Aggregation of dead shells might be invoked if, with very light valves, currents were sufficiently gentle for the surrounding aqueous medium to have an efficient cushioning effect against damage. With stronger currents or wave action breakage becomes more likely and it is difficult to credit that in an area of rapid sedimentation bordering a land of high relief currents strong enough to sort the detritus, as suggested by Wellman, Grindley, and Munden, would be gentle enough not to cause considerable damage of valves of *Monotis*.

At the south-western end of the Awakino gorge (Awakino Valley Road) the Warepan is 20 chains wide and the *Monotis* beds are in abrupt fault contact along their western flank with the Tertiary Mokau Formation. Although the fault must have had a downthrow of over 250 ft to the west, the Hokonui rocks appear little affected by it, no shattering, shearing, or slickensiding being observable even close to the fault plane. For a mile and a half north of the Awakino River the beds lie below a thin cover of Tertiary Mokau and Mahoenui strata, except in the Piripiri inlier, but then re-emerge and are exposed continuously northwards as a narrow meridional strip 30 to 40 chains wide lying above the Otamitan rocks and west of Turipoto Stream to beyond the area studied.

The regional strike is about 015° with local variations ranging from 010° to 025° and in Turipoto Stream faulting has given the older members strikes from 355° to 005°. The rocks in general dip eastwards at about 70°, although at the Turipoto Stream locality the faulting has overturned some beds to dip 55° west. The thickness of Warepan beds varies from 1,800 ft in Ballacraggan Creek to a maximum of 2,300 ft at the faulted Turipoto Stream locality. Henderson and Ongley

(1923) judged the thickness to be 600 ft of *Monotis* beds followed by 800 ft of unfossiliferous beds underlying Rhaetian plant beds.

The rocks are dominantly weathered, indurated, well-bedded siltstones or arenaceous siltstones with occasional thinner beds of sandstone and grit, tuffaceous in part. Many beds consist of crowded casts of *Monotis* set in a silty or fine sandy matrix, a condition typical of most other Warepan localities. A grit, or fine breccia, with shell fragments was the coarsest bed seen. It occurs in the south bank of Turipoto Stream in the lower part of the stage and becomes finer southwards along the strike. It is probably lensoid in character since it was not recognized south of this locality nor in Ballacraggan Creek, though its absence could be due to faulting.

Fossils occur plentifully at numerous horizons, though they are less common in the middle portion and none was found in the top 500 to 600 ft. The vast majority belong to the genus *Monotis* but a few other forms were also noted. Two fairly large though incomplete sequences were closely examined in the area and each will be dealt with in detail separately for the purpose of correlating and subdividing the beds.

Awakino Valley Road (*N91/555*)

The stratigraphic column (Fig. 5) illustrates the succession. The beds are cut off to the west by a fault and in places are covered by vegetation, but the outcrops enable a sequence of beds about 420 ft thick to be examined. This sequence is described from older to younger rocks and beds are grouped according to fossil content.

BEDS A: Fifty feet of beds, predominantly siltstones, lying east of the fault separating Tertiary and Mesozoic beds contain *Monotis ochotica densistriata* Teller. They strike 015° to 025° and dip at about 70° eastwards. The beds include a 3-ft band of grit, containing fragments of *Monotis*, angular quartz, and muscovite, which seems to be a channel filling, marking current erosion in newly laid beds.

BEDS B: The siltstones of Beds A are overlain by 12 ft of harder, less weathered siltstones. The outcrop is covered to the east so that the upper limit of this group of beds is not visible. The fauna consists of:

Monotis ochotica densistriata Teller
M. aff. *salinaria* (Schlotheim)
M. routhieri Avias
Monotis sp. A

BEDS C: An outcrop to the east of Beds B shows beds 12 ft higher in the succession, and consists of hard siltstones with casts of the following fossils:

Monotis ochotica pachypleura Teller
M. ochotica densistriata Teller
M. routhieri Avias
Monotis sp. A

BEDS D: East of Beds C the outcrop is cut off by a stream which creates a gap of 270 to 300 ft in the succession. Warepan rocks re-

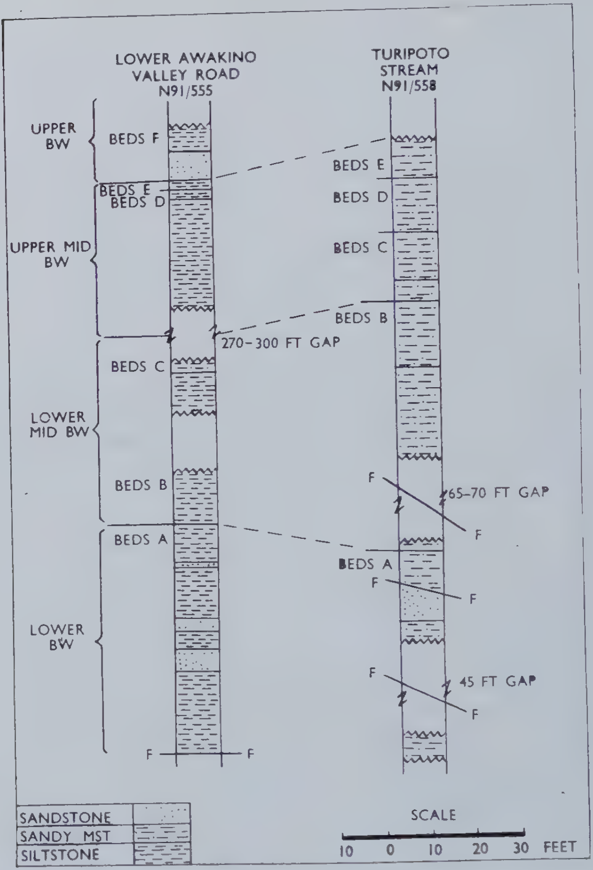

FIG. 5.—Stratigraphic columns and correlations of Awakino-Mahoenui Warepan sections.

appear farther east as a series of unfossiliferous well-bedded silstones overlain by 2 ft of shales with abundant but discrete *Monotis ochotica* cf. *gigantea* Avias.

BEDS B: The sequence is continued upwards by another set of shales with abundant scattered fossils. The fossil of Beds D is present in greatly reduced numbers and the common form is rather similar to *M. salinaria hemispherica* Trechmann.

BEDS F: The above beds are overlain by shales and indurated siltstones with thin grit bands and scattered fossils identified as the following forms:

Monotis ochotica Teller var.
M. salinaria, cf. *hemispherica* Trechmann
M. calvata Marwick
Monotis sp. B

East of these beds, although the outcrop continues for a number of yards along the road as almost vertical weathered brown shales, no fossils were found. These beds strike at about 025°.

Turipoto Stream Area (*N91/558*)

The beds are exposed along a track running across the strike of the rocks westward from a small tributary of Turipoto Stream some 65 chains upstream from its confluence with Manganui River. Of minimum thickness of 150 ft, the section is shorter than that exposed on Awakino Valley Road but it is more continuous, though at the western end it is cut into three small blocks by faulting. The following description proceeds from the base upwards and the groupings do not correspond with those of the last section. The succession is shown in Figs 5 and 6.

BEDS A: The outcrop consists of 8 ft of hard, weathered, arenaceous siltstones striking 010° and dipping eastwards at about 65°; the beds contain many large specimens of *Monotis richmondiana* Zittel. East of these beds the section is obscured for 50 ft by a mudflow containing angular fragments of tuffaceous grit, and fossiliferous siltstones re-appear farther east still striking at 010° but dipping westwards at 55°, which suggests that the beds are overturned, with the mudflow occupying the outcrop of a fault on fault-zone. The siltstone is overlain by a 7 ft band of weathered brown and white tuffaceous muddy sandstone, both sets of beds containing *M. richmondiana* and *M. salinaria* (Schlotheim). The sandstone is separated from the overlying siltstone by two faults with easterly downthrows shown by upward dragging of the easterly strata near the faults. These latter beds are less overturned than those to the west and dip

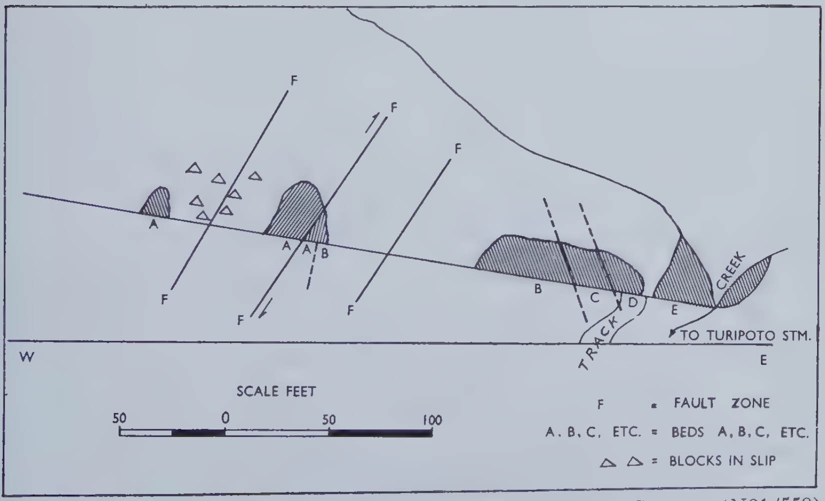

FIG. 6.—Diagrammatic sketch of Warepan near Turipoto Stream (N91/558).

80° eastwards. The minimum total thickness of this group of beds is between 40 ft and 70 ft.

BEDS B: Two feet of well bedded arenaceous siltstones occur above the top of Beds A and are crowded with casts of fossils. The succession is covered to the east for 65 to 70 ft by a large slip but these beds re-appear farther east and for more than 30 ft contain the same fauna. Here, however, faulting in the section obscured by the slip has again changed the attitude of the beds and the remainder of the sequence consists of beds with a meridional strike dipping 70° eastwards. The minimum thickness of the beds is probably about 55 ft.

Monotis richmondiana Zittel is still common but specimens are smaller than those in Beds A. Other forms found were *Monotis* spp. A and C.

BEDS C: Following Beds B are 15 ft of sediment of the same lithology as Beds B crowded with the following forms:

"Rhynchonella" sp.
Monotis ochotica gigantea Avias
M. ochotica Teller var.
M. salinaria hemispherica Trechmann
M. routhieri Avias
Monotis spp. A and C
Chlamys sp.

BEDS D: Above Beds C are 12 ft of partly weathered hard siltstone crowded with numerous casts of *Monotis ochotica gigantea* Avias and rare *M. routhieri* Avias.

BEDS E: From the top of Beds D to the western bank of the tributary of Turipoto Stream, where the outcrop ends, are 10 ft of very hard unweathered arenaceous siltstone with scattered fossils. The beds are more massive than the underlying beds, and contain the following forms:

Monotis ochotica gigantea Avias
M. salinaria hemispherica Trechmann
Monotis sp. B

The highest beds present in the lower Awakino gorge, containing *M. calvata* Marwick, are missing from the above section, although the small globose form (sp. B) found in them is present in Beds E of the Turipoto Stream section.

Restricted areas of Warepan rocks were examined at two other localities, but examination was brief and incomplete because of the steep and heavily-bushed nature of the region. The Piripiri inlier is the only area in which the transition from *Mytilus* to basal *Monotis* beds was seen. At the base of a 30-ft waterfall in very compacted unweathered arenaceous siltstones overlying unfossiliferous Otamitan beds were found a few specimens of *Monotis richmondiana* Zittel, very much smaller than is usual for the species. These lowest sparsely fossiliferous beds were not seen in Ballacraggan Creek. Here outcrops are fairly plentiful and although the sequence appears broadly similar to that of Turipoto Stream no more detailed collecting was done.

Subdivision of the Warepan Stage

Nearly all forms of *Monotis* in the area are common to both sections studied in detail. In general, where a form does not appear in one or the other, its absence can be explained on the grounds of incompleteness of outcrop. A notable exception exists in the cases of *M. richmondiana* and *M. ochotica densistriata*, each of which occupies the lowest beds of the Warepan, the former at Turipoto and Piripiri streams and the latter at Awakino Valley Road, and each ranges into overlying beds at its respective locality. Whether such mutual exclusion can be explained as due to difference of station is debatable, for the thickness of beds exposed and the lithologies are similar, and the localities are less than 3 miles apart along the strike. Some mixing of communities, as noted earlier, must occur and the two forms could confidently therefore be expected to be found together in at least some of the beds. Marwick (1946, p. 28) noted the occurrence of both forms together in the Marakopa district, north of the present area, but Avias (1953, p. 113) stated that what Marwick took to be *densistriata* was in reality Avias' *gigantea*.

Trechmann (1918) believed that *richmondiana* represented a lower horizon than *densistriata*, but the evidence in the Awakino district does not support this conclusion, since both forms appear representative of the lower Warepan. His conclusion was no doubt influenced by not finding the two forms together.

The beds overlying those with either *richmondiana* or *densistriata* are characterized by *Monotis* sp. A, as well as other forms including the two from the underlying beds. The next younger beds are characterized by the occurrence of *M. ochotica gigantea* Avias and are followed on Awakino Valley Road by an upper Warepan fauna with *M. calvata* which Marwick (1953) thought to be Otapirian and perhaps upper Warepan in age but which Campbell and McKellar (1956, p. 703) suggested to be Warepan. It has not been found associated with such typical Otapirian fossils as *Spiriferina* (*Rastelligera*) *diomedea* Trechmann or *Clavigera tumida* Hector, and, in New Caledonia, Avias (1953, p. 76) found it beneath beds with *Clavigera*. There appears to be no faunal evidence for placing beds with *M. calvata* in the Otapirian and from consideration of the apparent evolutionary continuity shown by forms of *Monotis*, *M. calvata* is here regarded as uppermost Warepan in age. Hence, since *M. calvata* is the last known representative of the genus found in New Zealand, the Warepan Stage corresponds closely with the teilzone of *Monotis*.

In summary, the four subdivisions of the Warepan recognizable in this area are considered below (Figs 5 and 6).

LOWER WAREPAN: This consists of Beds A of the Turipoto Stream sequence and Awakino Valley Road and contains the following forms:

Monotis ochotica densistriata Teller
M. salinaria (Schlotheim)
M. richmondiana Zittel

Beds of this age are probably 150 to 250 ft thick, sparsely fossiliferous in the lower part, but richly so in the upper.

LOWER MID WAREPAN: Beds of this group include those laid down from the first appearance of *Monotis* sp. A up to below those with the first representatives of *M. ochotica gigantea*. Beds belonging here on Awakino Valley Road have a minimum thickness of 40 ft, and in the Turipoto Stream section, of 55 ft. They contain the last representatives of *M. richmondiana* and *M. ochotica densistriata* as well as the following forms:

Monotis sp. A
M. ochotica pachypleura Teller
M. aff. *salinaria* (Schlotheim)
M. routhieri Avias
Monotis sp. C

UPPER MID WAREPAN: Beds included here consists of those laid down from the first appearance of *Monotis ochotica gigantea* until that of *M. calvata*. This includes Beds D and E of Awakino Valley Road and Beds C to E in the Turipoto Stream section, consisting of some 30 to 35 ft of strata. The fauna includes the following forms:

"Rhynchonella" sp.
Monotis ochotica gigantea Avias
M. ochotica Teller var.
M. salinaria cf. *hemispherica* Trechmann
M. routhieri Avias
Monotis sp. B
Monotis sp. C
Chlamys sp.

UPPER WAREPAN: Beds of this group include those laid down from the first appearance of *Monotis calvata* until that of the key Otapirian fossil *Spiriferina* (*Rastelligera*) *diomedea* Trechmann. The period is heralded by the extinction of a large number of the forms found in the underlying beds, only *Monotis salinaria* cf. *hemispherica* Trechmann and *Monotis* sp. C being able to survive. The fauna is much more retricted, a variety of *M. ochotica* being the only other *Monotis* present. The beds included here have a total thickness along Awakino Valley Road of a little over 500 ft, almost all apparently unfossiliferous.

With closer study of the faunas of other areas of Warepan rocks it should be possible to utilize the various forms of *Monotis* to build up a zonation of the stage. It should be noted in conclusion that, from stratigraphic data outlined above, Waterhouse's suggestion (1956, p. 589) that the New Zealand *M. ochotica densistriata* and *M. calvata* are the evolutionary equivalents of *M. ochotica gigantea* and *M routhieri* in New Caledonia cannot be substantiated.

OTAPIRIAN STAGE

The only fossils of Otapirian (Rhaetian) age collected by Henderson and Ongley (1923) were plant impressions from beds in the upper part of Ballacraggan Creek. These beds they correlated with similar beds outcropping on Manganui Road (N91/554) and 1½ miles up Kelly

Creek. The latter outcrop was not located, but evidence has been discussed above for regarding the Manganui Road beds as Oretian, and those in Kelly Creek are believed to be of a similar age.

The Otapirian Stage crops out in this area as a strip of rocks lying to the east of the *Monotis* beds and west of Awakino River. The strip is cut off to the south on the south bank of the river where it disappears beneath Tertiary Mokau sandstones and in Taumatamaire Road area it is covered by a thin layer of Tertiary mudstone and sandstone. Although not recognized, the stage is probably present in the north-east end of Piripiri inlier, as shown by the general attitude of the beds. Otapirian rocks strike at about 015°, dip 70° eastwards, and are 2,800 ft thick. They are exposed over a width of about 45 chains and are moderately fossiliferous. The sediments consist of well bedded indurated arenaceous mudstones and argillaceous sandstones and contain in places pyritic nodules, tuffaceous material, and carbonaceous remains. No conglomerates or grits were seen, although Henderson and Ongley (1923) recorded thick beds of conglomerate containing pebbles of granite, rhyolite, and dyke rocks, but did not give the locality.

In the present work a fairly full marine Otapirian sequence has been examined in the Awakino gorge and other localities in the area have been correlated with it. It has been possible to recognize both basal and upper Otapirian faunas, as did Campbell (1956), and also to differentiate mid Otapirian beds.

BASAL OTAPIRIAN BEDS: The lowest known Otapirian faunule in the area is in the headwaters of Ballacraggan Creek (N91/578), 550 ft above the *Monotis* beds, in a soft, weathered, greyish-white, sandy mudstone. The fossils collected from here, *Athyris* sp. and gen. et sp. aff. Pteriidae, allow correlation with the basal beds at Marakopa, where Mr J. D. Campbell (pers. comm.) collected similar large, flat athyrids. As already noted, plant beds occur in the headwaters of Ballacraggan Creek. Henderson and Ongley (1923) stated that they overlie *Monotis* beds by 600 to 1,000 ft and they thus appear to come somewhere closely above the *Athyris* beds. The writer has been unable to re-locate them.

In the Awakino gorge, wood fragments were found in argillaceous sandstones about 1,300 ft above *Monotis* beds and 100 ft below the lowest Otapirian fauna. The Warepan-Otapirian boundary in this part of the area is placed below these beds which possibly mark a shallowing of the Triassic seas and may also be of similar age to the Ballacraggan Creek plant beds. Future work, however, may well necessitate the shifting of the boundary to a lower horizon.

Although neither fossil of the faunule mentioned above has been recorded from the type locality nor mentioned in Campbell's (1956, pp. 49-50) list of basal Otapirian forms, correlation is possible with the Marakopa section and further work on Kawhia South Head and in beds on the eastern limb of the syncline in the south-west Auckland region could reveal the presence of the athyrid.

In the Awakino gorge the lowest Otapirian faunule found was in hard, dark grey, arenaceous siltstone about 1,400 ft above *Monotis* beds (N91/569) and consists of:

?*Climaconus* sp.
"*Rhynchonella*" sp.
Clavigera sp. juv.
Chlamys (s.l.) sp.

Nine hundred feet higher in the succession and 1,700 ft below the upper boundary of the stage, a brown weathered siltstone (N91/570) contains the following forms:

Spiriferina (*Rastelligera*) sp.
Kalentera n.sp.
?*Sisenna* sp.
Rissoa (s.l.) sp.

Five hundred feet stratigraphically above this siltstone the following fossils, with fragments of a small planispiral ammonite, were obtained from spheroidally weathered brown and grey siltstone and sandstone (N91/573):

"*Rhynchonella*" sp. B*
Spiriferina (*Rastelligera*) *gypaetus* Trechmann
Clavigera tumida Hector
C. cuneiformis Hector
"*Terebratula*" sp.
Chlamys sp.
Anodontophora aff. *angulata* Trechmann
Kalentera n.sp.

About 150 ft higher in the sequence beside Awakino Valley Road, *Anodontophora* aff. *angulata* Trechmann and *Anodontophora* sp. were found in hard blue-grey sandy mudstones (N91/581). Another 150 ft higher and 10 to 11 chains north-east of the last, *Palaeoneilo* sp. and *Pteria* sp. (apparently not the *P.* cf. *contorta* (Portlock) of the South Island basal Otapirian) were collected from grey-brown concretionary siltstones (N91/564), and the latter fossil was also found on the opposite bank of the river, 5 chains north along the strike.

Other Otapirian localities outside the Awakino gorge can be successfully fitted into the above sequence. The following fossils were found in a cutting on a track off Taumatamaire Road (N91/560) in weathered soft sandstone and siltstone:

"*Rhynchonella*" sp. B
Clavigera ? *cuneiformis* Hector
Kalentera n.sp.

In the gorge this fauna could be found anywhere in the 1,000 ft of strata above N91/573, but its position at about that horizon is indicated by the occurrence on Taumatamaire Road, a mile west of the tunnel at the head of the lower Awakino gorge, of *Anodontophora* aff. *angulata* Trechmann, which allows correlation with N91/573 or, more likely, N91/581.

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*This species also occurs at the type locality of the stage and is the *Rhynchonella* of Campbell (1956; pers. comm.) which constitutes a good mid and upper Otapirian marker. It is closely related to that at N91/569.

UPPER OTAPIRIAN BEDS: Some 300 ft stratigraphically above the beds at N91/564, and 25 chains north-north-east, occurs a fauna which, since it includes the lowest occurrence in the area of *Mentzelia kawhiana* Trechmann and *Otapiria dissimilis* (Cox), is of upper Otapirian age (Campbell, 1956). The beds are 550 ft below the top of the stage, and are hard grey-green siltstones and brown sandstones with small nodules of pyrite. They contain, in addition to the above two forms, the following fossils. (N91/563):

"Rhynchonella" sp. B
Spiriferina (*Rastelligera*) sp. juv.
Clavigera bisulcata Hector
C. cuneiformis Hector
Palaeoneilo sp.
?*Myophoria* sp. A

On the opposite bank of the river, 19 to 20 chains north-east of the last, the following forms were collected from grey argillaceous sandstone with small lenses of coarser, lighter-coloured tuffaceous material and abundant plant fragments (N91/574):

"Rhynchonella" sp. B
Clavigera cuneiformis Hector
"Terebratula" aff. *hungarica* Bittner
"Terebratula" sp.
?*Myophoria* sp. A
Anodontophora sp.
Kalentera n.sp.
Pleurotomaria 2 spp.

About 500 ft above these two, which are of approximately the same horizon, hard grey siltstone with pyrite nodules up to 1½ inches in diameter occurs in a high bluff at a sharp bend in the road (N91/562) and from it the following fossils were collected:

"Rhynchonella" sp. B
Mentzelia kawhiana Trechmann
Clavigera cuneiformis Hector
"Terebratula" 2 spp.
Otapiria dissimilis (Cox)
Kalentera n.sp.
"Trochus" sp.

Henderson and Ongley (1923, p. 20) recorded fossils, including *Athyris manzavinioides* (Trechmann) and *Halobia*, from beds at "the sharp bend of the Awakino River about a mile east of the quarry in *Pseudomonotis* beds". The locality is that of N91/562 above. Henderson and Ongley correlated the beds with those exposed in the quarry on Manganui Road (the Oretian N91/556) and explained their presence above *Monotis* beds by a fault (shown on their map). No evidence of faulting was seen and, on the contrary, the faunal succession indicates continuity. The most likely explanation of the record by Henderson and Ongley seems to be that the collection was wrongly labelled.

These beds represent uppermost Otapirian in the area, an Aratauran faunule occurring 40 ft higher in the sequence. It can be seen from the foregoing that the upper Otapirian faunas of the Awakino gorge show close correspondence with that defined by Campbell (1956), although this is not the case with the basal fauna.

Herangi Series

ARATAURAN STAGE

In the Awakino gorge, the only area of Aratauran (Hettangian-Sinemurian) rocks examined during this reconnaissance, the stage is represented by nearly 2,500 ft of hard fine sandstone, grey, pyritic and fairly massive at the base, but grey-green with flecks of lighter coloured material and more thinly bedded near the top. These beds crop out as a strip some 40 chains wide east of Otapirian rocks on the western side of the gorge. They disappear beneath the Tertiary cover south of the Awakino gorge and also north-west of it and, though they were not seen, must re-appear in the Herangi Range. Their general strike is 020° and they dip 70° to 75° eastwards.

Aratauran rocks are poorly exposed, only three outcrops having been located. Forty feet above the topmost fossiliferous Otapirian beds *Otapiria marshalli* (Trechmann) was collected (N91/589). The occurrence of this fossil, a good Aratauran marker, so close to the upper Otapirian beds, enables the Triassic-Jurassic boundary in the area to be fairly accurately located. There was continuous deposition and no change in lithology.

Some 2,100 ft above the base of the stage the following fossils were collected beside Awakino Valley Road 24 chains south-west of the junction with Awakau Road (N91/553):

Nodosaria 2 spp.
Dentalina sp.
?*Lagena* sp.
?*Vaginulina* sp.
Lenticulina sp.
?*Saracenaria* sp.
?*Frondicularia* sp.
2 spp. indet. Lagenidae
"*Rhynchonella*" sp.
Isocrinus n.sp.
Entolium fossatum Marwick
Pseudolimea sp.
Anodontophora (or *Pleuromya*) sp.
?*Cypris* sp.

Beds described above are included in the Aratauran partly on their stratigraphic position between definite Otapirian and Ururoan faunas. No psiloceratid ammonites were collected; *Otapiria marshalli* is a good Aratauran marker; *Entoluim fossatum* is also found in the Ururoan (see later). Foraminifera are not yet of much help in the New Zealand Jurassic because of lack of specimens and well identified forms.

URURỌAN STAGE

The Ururoan Stage has the following fauna (Marwick, 1953):

Rhynchonella bartrumi Marwick
Spiriferina radiata Hector
Pseudaucella marshalli (Trechmann)
Chlamys (*Camptochlamys*) *wunschae* Marwick
Pseudolimea inanis Marwick
Pleuromya urnula Marwick
Dactylioceras cf. *anguinum* (Reineche)

D. aff. *commune* (Sowerby)
D. aff. *timorense* (Boehm)

This fauna is actually composite, consisting of two faunules which have nowhere been recorded as occurring together. That of the lower beds consists of *Pseudaucella* and rare *Chlamys,* while that of the *Dactylioceras* beds (upper) never has either of those fossils.

In the Awakino area *Pseudaucella* is abundant but no *Dactylioceras* has been found. However, a faunule readily correlated with that of the *Dactylioceras* beds has been recognized and, as elsewhere, has no form in common with the underlying beds. Thus, in the area the stage is divided into lower Ururoan beds (Pliensbachian) and upper Ururoan beds (Toarcian).

LOWER URUROAN: In the area, beds of this age are defined as those laid down between the first appearance of *Pseudaucella marshalli* (Trechmann) and that of the genus *Dactylioceras.* In Awakino gorge, beds of Lower Ururoan age crop out along Awakino Valley Road on the eastern side of the river, for 3 miles from the junction of Awakau Road northwards to a quarry 1½ miles by road south of the tunnel, and they were recorded about 4 miles farther north on the southern slopes of the Herangi Range by Henderson and Ongley (1923, p. 20). The beds are exposed over a width of 25 chains and strike 018° near the base to 005° to 010° at the top, with easterly dips varying from 65° at the base to 55° to 60° at the top. In all, they are approximately 1,200 ft thick.

Apart from *Pseudaucella,* the only fossils found in the beds, mainly weathered siltstones and sandstones, were an unidentifiable pelecypod and an ammonite fragment, though Henderson and Ongley (1923, p. 24) also recorded *Corbicella* sp. Examination shows that, from lower to higher horizons, individuals of *Pseudaucella* show a size increase. In the lowest exposed beds they are less than ¼ in. long; slightly higher in the sequence they average ½ in. in length; while 900 ft higher the shell reaches a length of 1¼ in. This variation is less than that shown by the species in the Waikato area where it is found to increase from ¼ in. up to 2 in., but to have an uncertain stratigraphic value (Mr D. Kear, pers. comm.). Purser (1952) also noted a size increase in the Waikato South Head area. In the Hokonui Hills, dwarf *Pseudaucella* have been reported (Marwick, 1953, p. 23) with good *Chlamys wunschae.* Their stratigraphic value was in doubt because of the supposed occurrence of *Belemnopsis* in underlying beds. Mr I. C. McKellar (Dr J. Marwick, pers. comm.) has re-examined the locality and shown that the belemnite occurs well above *Pseudaucella.*

A section showing the boundary between upper and lower Ururoan beds is exposed on the roadside 1⅓ miles south-south-west of the tunnel at the head of the gorge. Henderson and Ongley (1923, p. 24) listed a composite fauna from this locality with fossils from both sets of beds. The upward sequence here is as follows. Thin bands of mudstone, sandstone, grit, and conglomerate pass abruptly to 20 ft of gritty and pebbly greensand, bedded at the base and massive above. This bed is overlain by a thin very weathered siltstone crowded with casts of *Pseudaucella,* followed by more greensand and then an unweathered, unfossiliferous compacted, carbonaceous obsidian breccia, consisting of discrete flakes and fragments of black obsidian, with their long axes lying in the bedding plane, and scattered elongate carbonaceous fragments, in a greenish sandy matrix. The top of this bed is regarded as the top of the lower Ururoan in the area and it is overlain conformably by thinly bedded siltstones with minor sandstone and grit, giving place to massive argillaceous sandstone. An almost vertical east-west fault dislocates the above beds. It has a down-throw of 10 ft to the north, on which side of the fault the thin *Pseudaucella* bed is enclosed in weathered, chloritic shear-zones which bend upwards to the fault.

UPPER URUROAN: Strata of this age are defined as those laid down between the appearance of the genus *Dactylioceras* and that of the genus *Inoceramus.* At the type locality of the stage (Ururoa Point, Kawhia South Head), these beds consist at least of the greensand with *Dactylioceras* and at the most include the 70 ft of sediments overlying it and below the reported occurrence of the Temaikan *Inoceramus* cf. *inconditus* Marwick (Marwick, 1953, p. 25).

In the area under review, *Dactylioceras* has not been collected, and the strata about to be discussed are correlated with those near Ururoa Point because of their stratigraphic position and the presence of a rhynchonellid known elsewhere only from the Ururoa Point greensand. Since beds correlated with the above are covered by Tertiary mudstone and limestone on their eastern edge in Awakino gorge, and since they were not located farther north in the Herangi Range, the full thickness of strata is not known and nowhere was the transition from these beds to those of the overlying stage examined, but they have a minimum thickness of a little over 600 ft. The upper boundary on the map (Fig. 2) has, therefore, been arbitrarily placed. The beds strike 015° and dip 55° east. They are very uniform in lithology, being somewhat massive, compacted and cemented, grey, argillaceous sandstone and arenaceous mudstone. Fossils are not plentiful but are found scattered through the beds. Because of the slightly calcareous nature of the rock these fossils do not occur as casts, as is usual in Hokonui beds. Microscopic examination of treated samples revealed no evidence of microfauna.

The earliest upper Ururoan fauna was found some 50 ft above the upper boundary of the lower Ururoan on Awakino Valley Road. The following forms, as well as an unidentifiable ammonite, were collected (N91/566):

"Rhynchonella" sp. C
"Terebratula" sp.
Palaeoneilo sp. A
?*Placunopsis* sp. A
Pseudolimea sp.
?*Astarte* sp.
Atractites sp.

From beds exposed 35 chains south of the tunnel in the gorge the following fossils, of a slightly higher horizon than the last, were collected (N91/567):

Palaeoneilo sp. A
Grammatodon sp. indet.
?*Placunopsis* sp. A
Amberleya sp.
Dentalium (*Laevidentalium*) sp.

The following faunule, of about the same horizon as the last, was found in beds outcropping beside the road ¼ mile farther south (N91/8):

"*Rhynchonella*" sp. C
Palaeoneilo sp. A
?*Placunopsis* sp. A
?*Amberleya* sp.

It was from this locality that Henderson and Ongley collected shells described by Marwick (1953, p. 108) as *Kalentera flemingi*. Re-collection by Geological Survey members in 1950 and 1954 and by the writer has failed to locate further specimens, each visit yielding a smaller fauna than the original.

In what are believed to be the highest beds exposed in Awakino gorge, 500 ft above the base of the upper Ururoan, cropping out on the road 30 chains north of the mouth of Mangaharuru Stream, the following forms occur, together with rare plant fragments (N91/565):

"*Rhynchonella*" sp. (also at Ururoa Pt.)
Spiriferina radiata Hector
Grammatodon aff. *montanayensis* de Loriol
Isognomon (?*Mytiloperna*) sp.
Entolium fossatum Marwick
?*Placunopsis* sp. A

Marwick (1953, p. 109) grouped rocks in this area containing *Kalentera flemingi* as Temaikan, but the presence of a rhynchonellid also found at Ururoa Point and of *Spiriferina radiata* enables correlation with upper Ururoan beds at Kawhia South Head. ?*Placunopsis* is the fossil recorded by Henderson and Ongley (1923, p. 24) as *Meleagrinella echinata* (Smith) and this record has been the basis for the Temaikan age allocation. Marwick (1935, p. 301), however, has already pointed out the differences from *Meleagrinella* and suggested generic relation with *Placunopsis*.

Kawhia Series

TEMAIKAN STAGE

The position of the upper boundary of the Temaikan Stage in the type sequence at Kawhia Harbour has been a matter of some confusion. Initially, Marwick (1951) included a black gritty fossiliferous sandstone on Totara Peninsula in the overlying stage but later (1953, p. 25) tentatively put the boundary of the stage above this bed. In the New Zealand fascicule (Ms) of the International Stratigraphic Lexicon Fleming included this bed in the lower Heterian, yet in the entry on the Temaikan Stage he gave without comment Marwick's placing of the Temaikan boundary above it. Fleming (pers. comm.) supplies the following sequence of beds on the south Kawhia shore: (1) thin marine beds with the type Temaikan fauna (*Meleagrinella*, etc.), (2) non-marine beds, (3) marine sandstone with *Inoceramus galoi*, *Epicephalites* and *Subneumayria*, (4) 2 to 3 ft bed of dark, gritty fossiliferous sandstone. The ammonites in bed (3) above are stated by Arkell (1956, p. 455) to be of lower Kimeridgian age. "This is our evidence for restricting Temaikan at Kawhia to bed (1) above, with the implication that with the non-marine beds above it covers the whole middle Jurassic plus Oxfordian" (Dr C. A. Fleming, pers. comm.). Thus, as had been done earlier, all beds containing *Inoceramus galoi* are referred to the Heterian, and the Temaikan Stage includes beds at the type locality up to below that with the lowest occurrence of *I. galoi*.

In the Mahoenui area neither the best indication of Temaikan beds, *Meleagrinella*, nor non-marine strata similar to those of the type locality have been found, and the presence of the stage here is based on the absence of *I. galoi* from beds east of (i.e. younger than) upper Ururoan. The absence of a particular form is not a satisfactory basis for correlation and further field work will possibly yield results necessitating alteration of the Temaikan-Heterian boundary in the area, but that, and the stratigraphic position, are the only criteria available at present for correlation. *Inocerami* have been collected from beds here classed as Temaikan but they are of such a fragmentary nature as to be of little help.

Strata correlated with the Temaikan were examined in two areas west and north-west of Mahoenui on the southern and south-eastern flanks of the Herangi Range. The sequence examined in the former area, the Stony Creek-Ototohu Stream region, is of less stratigraphic extent than that seen on and near Upper Awakino River Road. Because of the precipitous slopes and dense bush, beds comprising the remainder of the Herangi Range were not examined, but they probably make up a thickness of about 2,500 ft, consisting mainly of Temaikan strata.

The beds examined have a total thickness of about 2,000 ft in Upper Awakino River Road vicinity and 1,150 ft in Stony (Rauroa) Creek. Dips vary from 20° to 45°, with 30° common. Strike measurements in the two districts are somewhat different, measurements in the former giving a meridional strike and those in the latter giving results varying between 025° and 050°. An east-west fault was noted in the Stony Creek area and it is presumed that this has caused the variation in strike, as well as possible repetition of some strata.

Indurated siltstones predominate in these beds, with occasional sandstones and less frequent grits or conglomerates. In addition, unidentifiable plant remains and tuffaceous bands were noted at a few localities.

The strata lowest in the succession were seen in the beds of streams flowing eastwards into the Awakino River in the north-east of the area. The oldest of these is a 30 ft-thick unfossiliferous, massive grey sandstone cropping out 1 mile 30 chains up a stream which enters the

Awakino River 1½ miles north-east of Herangi Trig, and occurring 2,000 ft below the Temaikan-Heterian boundary. It is overlain by blue mudstone and, 10 chains downstream, by a 10 ft-thick concretionary blue-grey siltstone cut by calcite veins and containing an indeterminable *Grammatodon* (*Indogrammatodon*) (N91/505). Twenty-five chains downstream from this bed this siltstone is overlain by a more fossiliferous spheroidally weathering siltstone from which was collected the following fauna (N91/599):

Grammatodon (*Indogrammatodon*) sp. A
Myophorella (*Scaphogonia*) sp.
Pleuromya milleformis Marwick
Astarte spitiensis Stoliczka

The next beds encountered, 14 chains farther downstream, were hard unfossiliferous blue-grey sandstones overlain by a blue arenaceous mudstone with close, thin, carbonaceous layers about 1,000 ft below the top of the stage. Beds of about the same horizon crop out beside Upper Awakino River Road a mile south of the northern boundary of the area, where *Pleuromya milleformis* Marwick was collected from a weathered siltstone with thin sandy lenses. Some 200 ft higher in the sequence a brown sandstone in the above-mentioned stream, 28 chains from the mouth, is overlain by a 15 ft thick bed which grades from a fine conglomerate with abundant plant fragments at the base to a fine hard grit. Ninety-six chains south of here, in the bed of a stream draining east from Trig S, an unidentifiable pelecypod was found in brown siltstones containing plant fragments and of about the same horizon as the last. Also somewhere about this horizon or slightly higher, Henderson and Ongley (1923, p. 24) collected 10 species of Brachiopoda and Mollusca, including *Arca, Astarte, Pleuromya,* and *Inoceramus ?brownei* Marwick, from a conglomerate on the Awakino River bank near Gribben's homestead (G.S. 980). These beds are about 700 ft below the upper boundary of the stage and were taken by Henderson and Ongley as marking the base of the upper Jurassic in this area.

Some 250 ft higher in the sequence, and ½ mile southwards along the bank of the Awakino River, a hard, gritty, blue sandstone containing many greywacke pebbles and rare brachiopod, pelecypod and belemnite fragments was seen while the highest Temaikan beds, 420 ft higher and 50 ft below the top of the stage, were found to be indurated unfossiliferous gritty tuffaceous sandstone which crop out beside the road a farther ½ mile southwards.

The lowest beds seen in the Temaikan sequence in Stony (Rauroa) Creek are 1,150 ft below the Temaikan-Heterian boundary. They are unweathered, very hard, grey, gritty sandstones with the following fauna (N91/591), 50 chains upstream from the ford on Taumatamaire Road:

Grammatodon (*Indogrammatodon*) sp. A
Myophorella (*Scaphogonia*) sp.
Pleuromya milleformis Marwick
Astarte spitiensis Stoliczka
?*Tellina* sp.

Pleurotomaria (*Perotrochus*) sp.
Pachyteuthis sp.

These beds are overlain for at least two chains downstream by hard, blue, fine sandstones and concretionary siltstones with rare *Pleuromya milleformis* Marwick. Six chains downstream occur an unfossiliferous green sandstone and a brown siltstone with plant fragments, the latter being overlain two chains downstream by green and brown barren grits and then by a hard blue siltstone. Some 12 chains downstream and 500 ft above the base of the sequence occur brown sandstones and siltstones with *Hibolithes* aff. *catlinensis* (Hector) (N91/590). At the same horizon and 22 chains east-north-east the following fossils were collected from weathered mudstone (N91/584):

Nucula (*Palaeonucula*) *cuneiformis* Sowerby
Inoceramus 2 spp.
Variamussium clamosseum Marwick.

About 5 chains downstream from N91/590 a foot-thick shellbed with sandy and muddy matrix, here termed the Rauroa Shellbed, was seen. It is in a sequence of alternating weathered sandstones and siltstones and contains the following large fauna (N91/588):

Rotularia sp. A
Serpula aff. *limax* Goldfuss
"*Rhynchonella*" sp.
"*Terebratula*" sp. B
Nucula (*Palaeonucula*) sp.
Palaeoneilo sp.
Parallelodon sp.
Grammatodon (*Indogrammatodon*) n.sp. B
Arca sp.
Inoceramus sp. indet.
Isognomon sp.
Mytilus sp.
M. (*Pernomytilus*) sp.
Pleuromya ?*milleformis* Marwick
Astarte sp.
Eucyclus sp.
?*Promathilda* sp.
?*Partschiceras* sp.
?*Pseudocadoceras* 2 spp.
Hibolithes sp.

Since the entire fauna with the possible exception of the *Pleuromya* is apparently new to New Zealand, little help is at present gained for precise age determinations but work is proceeding on the ammonites which seem to indicate a Callovian age. At about the same horizon and 4 chains north-east the same terebratulid and *Pleuromya milleformis* Marwick were found in interbedded weathered sandstone and siltstone. Four chains downstream from here, beds of the same lithology contain an unidentifiable cephalopod and the following (N91/582):

Rotularia sp. A
Serpula aff. *limax* Goldfuss
"*Rhynchonella*" sp.
"*Terebratula*" sp. B
Grammatodon (s.s.) sp. indet.
Pleuromya milleformis Marwick

?*Promathilda* sp.
?*Dentalium* (*Laevidentalium*) sp.

Very little higher in the sequence and 4 chains north-east, the following fossils were collected from a weathered, green, carbonaceous, greywacke grit (N91/583):

Rotularia sp.
Isognomon sp.
"*Ostrea*" sp.
Entolium sp.
Camptonectes aff. *grandis* (Hector)
Variamussium clamosseum Marwick

Weathered interbedded tuffaceous sandstones and siltstones outcrop 4 chains farther north-east. An almost vertical east-west fault cuts these and the overlying Tertiary beds. The former show slickensiding and the latter, limestones of the Te Kuiti Formation, on each side of the valley of Stony Creek show a perceptible change of dip, though no vertical dislocation seems to have occurred. Whether or not much relative vertical movement of the Hokonui beds on either side of the fault took place in pre-Te Kuiti times is not obvious, but this very likely has some bearing on the noted change of strike in this area. These beds are some 200 ft below the upper boundary of the stage in the district.

HETERIAN STAGE

As noted earlier, the base of this stage is marked by the incoming of *Inoceramus galoi* Boehm, and quite possibly some of the beds discussed under the previous stage may, by more field work, be shown to be better placed here. The base of the overlying Ohauan Stage is marked by the presence of *I. haasti* Zittel but since neither this nor any other typically Ohauan fossil has been found the remaining beds of the Hokonui System in the Awakino-Mahoenui area are referable to the Heterian Stage.

The strata included here have a minimum thickness of 4,300 ft north-north-west of Mahoenui, though only 2,600 ft of the basal beds are exposed in the Ototohu Stream area west of Mahoenui, the upper beds in each area being hidden by the overlying Tertiary beds. The beds strike approximately meridionally and dip eastwards at angles varying from 45° near the base to 15° near the top as the axis of the syncline is approached. As with Temaikan beds, siltstones predominate but sandstones, grits, and conglomerates occur occasionally in the sequence and plant remains are also present. The beds are hard and indurated when unweathered but become soft and rather muddy on weathering. Calcareous material is not uncommon but microfaunas are apparently absent.

The lowest occurrence of *Inoceramus galoi* Boehm is in weathered siltstone on the bank of a small creek draining underground between Stony Creek and Ototohu Stream and the following additional fossils were also collected here (N91/586):

Rotularia sp. A
Grammatodon sp. indet.
Inoceramus sp.
Belemnopsis sp. A

The *Inoceramus* was also collected in Ototohu Stream 56 chains north-east, from weathered brown siltstones (N91/601). In the Waikato South Head district the same fossil was reported from beds of lower Heterian age (Purser, 1952). A similar, though apparently not identical, small *Inoceramus* was found with *Grammatodon* (*Indogrammatodon*) n.sp. B in beds of the same lithology 12 chains southwards (N91/587), while a further 12 chains south-east an *Inoceramus* having much in common with the Ohauan *I.* aff. *everesti* Oppel was found in a boulder in Ototohu Stream. This shell could be either Temaikan or Heterian in age. The highest beds seen in Ototohu Stream, some 1,800 ft above the lowest occurrence of *I. galoi* consist of brown siltstones with carbonaceous fragments but no animal remains.

On Upper Awakino River Road the lowest Heterian beds are marked not by *I. galoi* but by *Buchia malayomaorica* (Krumbeck) which is a good upper Jurassic marker. These beds are coarse conglomeratic sandstones with the following additional fauna (N91/598):

"Rhynchonella" sp.
Pleuromya milleformis Marwick
Astarte sp.

Fossiliferous beds were not again found until 55 chains south along the road and some 1,330 ft higher in the sequence the following forms were collected from a soft spheroidally weathered siltstone (N91/597):

Palaeoneilo sp.
Grammatodon (*Indogrammatodon*) n.sp. B
Inoceramus galoi Boehm
Buchia malayomaorica (Krumbeck)
?*Kossmatia* sp.

Sixty-five chains farther south the beds are unfossiliferous brown siltstones which at the mouth of Palmer Creek, are overlain by hard, blue-grey, concretionary siltstones. These beds also crop out on upper Awakino River Road and contain (N91/594):

Inoceramus galoi Boehm
Pleuromya milleformis Marwick
Belemnopsis sp. A

One and a half miles north of the mouth of Palmer Creek and at the same horizon as the last the beds are cut by calcite veins in which occur small aggregates and crystals of pyrite. The following fossils occur in the calcareous concretions (N91/600):

Inoceramus galoi Boehm
Buchia malayomaorica (Krumbeck)
Lewisiella (*Aulacotrochus*) sp.

Thirteen chains up Palmer Creek from the mouth, the siltstone is overlain by a hard, blue sandstone and this, 4 to 5 chains upstream, by a very weathered greywacke conglomerate which gives place to a hard, black, (?) glauconitic, gritty sandstone with numerous well preserved fossils, here called the Palmer Creek Shellbed (N91/595). The fauna includes:

Pyrgopolon sp.
Myophorella (*Vaugonia*) *kawhiana* (Trechmann)
Inoceramus galoi Boehm
Camptonectes cf. *laminatus* (Sowerby)
Pleuromya milleformis Marwick
Astarte spitiensis Stoliczka
A. morgani (Trechmann)
Pseudomelania (*Rabdoconcha*) sp.
Cerithinella sp.
Belemnopsis 3 spp. (including sp. A)

This locality was visited by Henderson and Ongley, who listed (1923, p. 24) 9 species from the bed, whose lithology and fauna leave little doubt that it is the exact equivalent of the dark gritty fossiliferous sandstone of Totara Peninsula, Kawhia Harbour, of lower Heterian age. The Palmer Creek Shellbed crops out for 2 chains upstream and is overlain by a less fossiliferous finer sandstone which, 1½ chains farther upstream, passes into a hard unfossiliferous sandy siltstone. These beds are 3,500 ft above the base of the stage, so it is apparent that lower Heterian sedimentation was much more rapid in this area than at the type locality where there is only some 500 ft of sediment, including Temaikan, between the type Temaikan fauna and that of the sandstone at Totara Peninsula.

Twenty-five chains upstream from the Palmer Creek Shellbed and 200 to 250 ft higher a hard, blue-grey siltstone contains the following fauna (N91/596):

Inoceramus galoi Boehm
Buchia malayomaorica (Krumbeck)
Camptonectes cf. *laminatus* (Sowerby)
Lima sp.
Pleuromya milleformis Marwick
Belemnopsis sp. A

This locality is that from which Henderson and Ongley (1924, p. 23) reported *Kossmatia* aff. *desmidoptycha* Uhlig (as *Ammonites novozelandicus* Hauer—see Marwick, 1953, p. 121) of Geological Survey collection G.S. 982. Marwick recorded this ammonite as of upper Heterian (?Tithonian) age. These beds continue for about 20 chains upstream and are in places concretionary. They include minor sandstones, fine grits, and greywacke conglomerates, as well as the dominant siltstones.

The same beds, though here weathered and brown, crop out on upper Awakino River Road and contain the following forms (N91/593):

"Terebratula" sp.
Inoceramus galoi Boehm
Buchia malayomaorica (Krumbeck)
Pleuromya milleformis Marwick
Belemnopsis sp. A

The highest fossiliferous horizon located in the area, 4,150 ft above the base of the stage, crops out a further 15 chains south-east along the road. Here a weathered brown siltstone is overlain by a thin intraformational conglomerate, then by a greyish brown unfossiliferous sandstone, and contains the following fauna (N91/592):

Inoceramus galoi Boehm
Camptonectes cf. *laminatus* (Sowerby)
Pleuromya milleformis Marwick
Cerithinella sp.
Belemnopsis sp. A

The same *Cerithinella* has been collected from Moewaka Quarry, Waikato South Head area, 1,000 ft below the base of the Ohauan (Purser, 1952). Marwick (1953, p. 126) recorded the beds of this quarry as being of Temaikan age but since the fauna includes *Inoceramus galoi* (Purser, 1952) the beds should be included in the Heterian Stage.

The only Hokonui rocks seen above this horizon crop out 35 chains farther south-east along the road, about 20 chains north-west of the point on the road where the Hokonui rocks disappear beneath Tertiary sediments, and nearly 200 ft stratigraphicaly above the last locality. The strata consist of hard, grey and brown, unfossiliferous sandstones.

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HEAVY MINERALS FROM SOUTHLAND

PART II: UPPER CRETACEOUS-LOWER TERTIARY COAL MEASURES

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Summary

Heavy minerals from coal measure sandstones near Ohai, Tuatapere, Orepuki, Waimumu, and Gore form distinct suites, in most cases derived from immediately adjacent older rocks. This restriction of parent detritus to limited distributive provinces facilitates paleogeographic reconstruction of small, isolated, coal measure basins at the onset of Tertiary sedimentation. Samples from stratigraphically higher marine beds indicate a more even spread and an admixing across Southland of detritus which represents mineralogically three areas of provenance: Fiordland metamorphics and intrusives, Otago schists, and Permian-Jurassic sediments.

Introduction

The period of sedimentation which commenced the Tertiary succession in Southland followed after the folding and erosion of the undermass resulting from the Hokonui orogeny in the late Jurassic or early Cretaceous. Localized areas of coal measure sediments, upper Cretaceous to lower Tertiary in age and separated from the undermass by marked unconformities, form the basal beds of the Tertiary sequence. The heavy mineralogy of these beds is now described and the results discussed in terms of provenance by comparing the heavy concentrates with those of the Permian-Jurassic sediments (Brothers, 1959) and with recorded descriptions of metamorphic and igneous rocks in the undermass.

The sediments of the various coal measure basins have in common many textural features, such as angularity and coarseness of grain, and lack of sorting at most horizons, but they differ in each case by showing a heavy mineral content with affinities to the mineralogy of the rock type of the undermass situated nearest to the basin. The commonest sandstones in the coal measures are quartz-feldspar-biotite rocks with poorly sorted angular grains set in a chloritic clay matrix. The coal measures sampled are located at Ohai, Tuatapere, Orepuki, Waimumu, and Gore.

Ohai Coal Measures

Lillie (1950) sets out the general succession at Ohai as follows:

(5)	Shelly limestone bands	100 ft
(4)	Marine mudstones with Whaingaroan microfaunas	1,100 ft
(3)	Freshwater mudstones and clay ironstones	2,300 ft

(2) Coal measures, consisting of sandstones, conglomerates, mudstones, claystones, and thick lensing seams of coal .... 1,050 ft

(1) The basal beds rest unconformably on greywackes and porphyrites, the greywackes having yielded good Triassic fossils at the base of a bore through the measures, as well as in adjoining outcrops.

The measures are exposed in the valley of Ohai Stream, and sandstones from a number of bore cores and mine samples were combined to give the results shown in Tables 1 and 2. Two sets of samples were taken: one from the north side of the coalfield in the vicinity of Linton and Birchwood mine workings (Table 1), and the other from the south side, near Star and Wairaki (Table 2).

TABLE 1.—Heavy Mineral List for Ohai Coal Measures, Section from South Side of Coalfield.

	S 168/1918	S 168/1019	S 168/1021	S 168/1020	S 168/1012	S 168/1013	S 168/1014	S 168/1015	S 168/1016	S 168/1017	S 168/1009
Andalusite			r								
Apatite	50·2			25·3	13·2	1·3	6·0				r
Biotite	5·4	r	r	1·1	r	r	r	r		r	r
Chlorite			r	r		r		r		r	r
Epidote		r				r	r		r	r	43·4
Garnet	r	r	r	r	r		r	r		r	r
Hornblende	r	r	r		r			r		r	r
Iron ore	30·3	6·8	75·7	47·6	68·5	3·1	52·5	90·6	8·8	74·6	50·7
Kyanite						r					r
Rutile				r	r	r		r			
Sidero-dolomite		76·7	r	15·5	r	92·0	32·9		86·1	r	
Sideroplesite		r	r	r		r			r	20·8	
Sphene	3·7	14·0	15·9	r	12·6	1·8	4·7	r			r
Topaz											?
Tourmaline	r	r	r	r	r	r	r	1·1		r	r
Zircon	9·5	r	8·1	9·0	5·0	1·1	3·5	7·3	5·5	3·8	3·6
Zoisite											r
Biotite	c	f	f	f	r	r	r	r	r	r	r
Calcite				f		r	r				
Chlorite	r	r	r	f	r	r	r	r		r	r
Feldspar	r		r	c	r	r		r	r	r	r
Muscovite	r	r	r	r	r		r				r
Quartz	c	c	c	c	c	f	r	c	c	c	c
Siderite		r		f	r	c	c		f		
			No. 1 Star Seam				Interval 240 ft			No. 2 Wairaki Seam	

TABLE 2.—Heavy Mineral List for Ohai Coal Measures, Section from North Side of Coalfield.

Sample No.	S 168/1029	S 168/1027	*S 1681027*	*S 168/1023*	S 168/1022
Andalusite					
Apatite	r	44·1		60·5	2·0
Biotite	r	4·5	18·4	5·9	r
Chlorite	r	r	r	r	1·5
Epidote					
Garnet		r		r	r
Hornblende					
Iron ore	35·7	42·8	62·1	18·3	2·7
Kyanite					
Muscovite	3·9		15·7		
Rutile			r	r	
Sidero-dolomite	35·8			r	92·1
Sideroplesite	r				r
Sphene					r
Topaz					
Toumaline	r	r	r	1·4	r
Zircon	22·5	8·3	3·2	13·4	1·3
Zoisite					
Biotite	r	c	r	c	f
Chlorite	r	r	r	r	f
Feldspar	r	r		r	r
Muscovite			r	r	r
Quartz	c	c	c	c	c
Siderite	r				
			Birchwood Seam No. 1	Linton Seam No. 2	

In general, there is a marked similarity between these concentrates and those already described from the Permian-Jurassic sediments (Brothers, 1959). This is indicated by the range of grain size, and other specific characteristics, of the minerals, zircon, apatite, epidote, and some garnets. Colourless or pink garnets are present both as ragged, pitted grains and as sharply euhedral crystals. It is likely that the spinose and worn grains were derived from adjacent Mesozoic sediments, but the euhedral crystals probably originated from the same metamorphic source as the blue tourmaline—andalusite—kyanite assemblage. The euhedral form of the garnet is always {110}, with or without minor trapezohedral faces; similar euhedra of garnets were recorded by Hutton (1950) in the Central and Western Otago schists and in the Fiordland gneisses. The rare grains of blue-green hornblende, in the form of elongated fibrous plates with dentate ends, probably came from a Fiordland-type source rock, but show the effects of weathering and abrasion more readily than do the euhedral garnets.

Elongated prismatic grains of tourmaline, terminated by cross-fractures to (0001), exhibit dimensions up to 2·16 mm × 0·77 mm. Although there is a resemblance, in the relative amounts of tourmaline present, between the coal measures and the Mesozoic sediments, in the younger rocks the mineral is larger in grain size and possesses a much wider range of pleochroic schemes. Nine dichroic groups were recognized: colourless to green (c), blue (r) or light brown (c); grey to pink (r); pink to deep green (c) or blue (r); light blue to deep blue (c); brown to green (c) or black (a).

All varieties persist from the lowest to the highest horizons, but vary in relative abundance as indicated by the letters (a) = abundant, (c) = common, and (r) = rare. Authigenic tourmaline appears as long and delicate, acicular crystals built out from apparent parent grains with which they show no optical continuity, but outer layers of tourmaline formed around older corroded grains of the brown–black pleochroic variety are also possible authigenic additions. In both cases, the secondary tourmaline has the pleochroic scheme pink to blue.

Minerals of the siderite—dolomite group, entirely authigenic in origin, have the form of small grains with rhombohedral cleavage, or else occur in botryoidal masses with encrusting small spinose crystals. Replacement of quartz and feldspar by these carbonates is not uncommon. Specific gravity varies from below that of tetrabromethane (2·965), at the dolomite end, to higher values, and refractive index changes from lower to higher than canada balsam. Within this group of carbonates, sideroplesite (Gregory, 1910; Hatch and Rastall, 1913) was separately distinguished from the trigonal members by its outstanding hexagonal habit. The golden brown to lemon yellow shell surrounding an opaque core and containing zonary and radiating structures is characteristic.

Irregular angular fragments of yellowish to golden sphene, with maximum size 0·52 mm by 0·36 mm are detrital grains. Brown and yellow-brown varieties form authigenic granular aggregates which carry adherent, small, sharp euhedrons of sphene, and often enclose large patches of ilmenite in a similar fashion to the secondary titanite described by Brammall (1921).

Conclusions

Boulders of schist in conglomerates near the faulted edges of the coalfield and in bore cores from near the base of the coal measures indicate that a strong metamorphic element should be present in the heavy mineral separates. Criteria for metamorphic and acid igneous provenance in the concentrates are:

(a) a large number of pleochroic varieties of tourmaline not known in the greywackes, but recorded from the Otago schists (blue tourmaline) and the Fiordland rocks (brown tourmaline);

(b) the presence in one sample of both weathered and euhedral garnets, the latter being regarded as fresh detritus from a metamorphic terrain;

(c) the presence of kyanite, andalusite, and detrital sphene;

(d) the abundance of quartz in angular fragments poekilitically enclosing hornblende, rutile, and tourmaline, and of complexly sutured grains of quartz.

The following features indicate derivation of detritus from the Permian—Jurassic sediments:

(a) comparably large quantities of a few minerals like apatite, zircon, and opaque ores dominate the heavy concentrates;

(b) similar varieties of apatite and zircon with secondary outgrowths, although in the case of zircon some of the authigenic additions may have been made within the Tertiary sediment;

(c) deeply etched garnet;

(d) apparently derived, composite grains of authigenic epidote.

The metamorphic detritus diminishes in quantity above the base of the coal measures, where there is a richness in the heavy mineral suite that does not appear again at higher levels. However, rapid lateral changes in the nature of the heavy concentrates are common in the Ohai sediments and a vertical series of samples from elsewhere in the coalfield may provide suites in which minerals, derived from the adjacent Mesozoic sediments, are dominant.

TUATAPERE COAL MEASURES

Tuatapere is situated about 20 miles south-west of Ohai and the coal measures are located a few miles to the north of the township. The sediments are poorly exposed, being confined to lowland country in the angle formed by the confluence of Waiau and Orauea rivers and to foothills on the west side of Longwood Range. Structural details are unknown, but, where sampled, the indistinct bedding gave a strike of 042° and dip 15° north-west. The results of heavy mineral analyses are shown in Table 3 under sample numbers S 167/1008, which represents the average of four samples taken at intervals of 50 ft across the strike of beds exposed in a cutting on the Tuatapere—Invercargill railway line. The sandstones are unfossiliferous, generally massive rocks similar to those of the Ohai group.

Detrital grains of titanite, hornblende, epidote, and biotite dominate the heavy concentrates. The hornblende is mainly a blue–green variety in large grains measuring up to 1·08 mm by 0·63 mm. A greenish-brown variety occurs in minor amount. Epidote is present in the rounded composite type of grain and as glossy green "bottle-chips" of iron-rich composition. Biotite is brown to green in colour, the red variety not being present. Pink garnet consistently has the form of fresh {110} euhedra with occasional traces of strain polarization. In contrast to the

Ohai samples, zircon is present in very minor amount and the grains are confined to — 60 and + 200 mesh grades. Sutured masses of strained quartz make up the bulk of the light concentrates.

Conclusions

Adequate sampling at depth would probably alter greatly the percentages of heavy minerals shown in the list. Nevertheless, there is a marked difference between this assemblage and that of the Ohai coal measures, and it appears that the distributive province of detritus supplied from the Permian—Jurassic rocks did not extend to the Tuatapere basin. Mineralogical evidence for this deduction is the abundance of fresh hornblende of a type that is common to the Fiordland rocks (Hutton and Turner, 1936), and the presence of andalusite, euhedral garnet, and allogenic titanite and epidote. Relative absence of zircon and apatite points to the same conclusion. An interesting similarity may be noted between sample S 167/1008 and three samples from fossiliferous marine beds of upper Oligocene age described by Hutton and Turner (1936) from Clifden, 8 miles north-east of Tuatapere. The main differences are a higher degree of grain rounding and the occasional presence of pyroxenes in the Clifden sediments.

WAIMEAMEA COAL MEASURES

Samples of sandstone were taken from near the base of the coal-bearing strata in the Waimeamea Series which overlies an igneous complex close to Orepuki. The following is a generalized section of the Waimeamea Series after Willett and Wellman (1940):

Orepuki Series
(Unconformity)

Waimeamea Series
Fossiliferous sandstones (Duntroonian = upper Oligocene)
Argillites and igneous conglomerate.
Mudstones with carbonaceous lenses.
Coal and Oil-shale.
Sandstones.
(Unconformity)

Basal igneous complex, consisting of granites, acid diorite, gabbros, and norites, which, when seen immediately underlying the Tertiary sediments, are extensively weathered. These igneous rocks were intruded into greywackes and argillites of Te Anau Series (Permian).

The lower sandstones of Waimeamea Series were sampled at Hennessy's coal mine, Waimeamea River, at one of the few good exposures of the coal measures beneath the general cover of Orepuki Series.

The heavy minerals from the sandstones (S 175/1004), Table 3, are similar to those from Tuatapere. Epidote is in clear crystal fragments and tourmaline is a light brown to black variety. In contrast with the Tuatapere assemblages, there is a higher percentage of zircon and a lack of fresh garnet crystals. Hornblende is the dominant non-opaque mineral and occurs in greenish brown to deep green elongated grains which mostly are subangular. Schistose quartz is rare in the light concentrates, the quartz fragments being large and angular with inclusions of hornblende, rutile, tourmaline, and (?)cordierite.

Oil-shales are closely associated with the coal seams. At Hennessy's mine, the shale is only a few inches thick, but in a cutting made during the operation of an extraction plant several miles to the south-east near Taunoa Stream the bed is 4 to 5 ft thick.

Sample S 175/1005 came from the latter locality. Prior to disaggregation, traces of residual oil were removed by benzene distillation and the grains were later washed in benzene to remove carbonaceous coatings. Heavy detrital minerals are rare in the shale, but their character is in keeping with that of the minerals recorded from the basal sandstones at Waimeamea River. Titanite forms irregular authigenic patches and the opaque ores are mainly ilmenite and rare pyrite. Andalusite and augite, in large rounded grains, are not represented in the heavy suite of the basal sandstones.

Conclusions

The mineral assemblages may be compared favourably with those from Tuatapere, where there is a similar abundance of hornblende and allogenic epidote. Minor differences appear in the nature of the raw minerals. A local area of provenance in Fiordland-type rocks and the Longwood plutonics, rather than in Permian-Jurassic sediments, must be assumed for the detritus, particularly since green hornblende, brown tourmaline and andalusite are present, and apatite is absent.

WAIMUMU COAL MEASURES

The analysis (S 169/1000) given in the mineral list of Table 3 represents an average of three samples of medium-grained sandstone taken from different levels in the coal measures at Waimumu, 30 miles north-east of Invercargill. The lithology of the sediments is similar to that of coal-bearing rocks elsewhere in Southland. Beds exposed in the present workings and in old pits along the Hedgehope Road grade from a muddy facies to coarse-grained sandstones, which are lensoid and either current-bedded or massive.

Apatite, garnet, tourmaline, and zircon are almost identical in habit and optical properties with the same minerals in the Permian-Jurassic sediments. Titanite, in association with granular ilmenite, is mainly authigenic in origin. The very high proportion of opaque minerals in the heavy concentrates consists mainly of ilmenite in all stages of alteration to leucoxene and emphasizes the paucity of the non-opaque assemblage.

Conclusions

When allowance is made for re-washing, there is no great mineralogical difference between the Waimumu coal measures and the nearby Mesozoic sedimentary rocks. In the mineral lists, the Waimumu heavy suite stands out in strong contrast to those from Tuatapere, from the base of the Ohai succession, and from Orepuki, in all of which a dominantly metamorphic or acid igneous area of provenance is represented. In the present case, the evidence is suggestive of contamination of the greywacke detritus by material derived from the Otago schists in the form of blue tourmaline and small quantities of schistose quartz.

GORE LIGNITE MEASURES

Samples S 170 1001 and S 170/1002 (Table 3) came from low-lying formations a few miles north-east of Gore at the respective grid references S 170/905518 P, S 170/857453 P, and were mapped by Wood (1956) as the Gore Lignite Measures. In each of two localities in road cuttings, four miles apart, a series of two samples was taken over a vertical interval of 20 ft. The extreme similarity between the heavy minerals from the two outcrops allows these rocks to be regarded as mineralogically identical.

TABLE 3.—Heavy Mineral List for Tertiary Sediments.

	S 167/1008	S 175/1004	S 175/1005	S 169/1000	S 170/1001	S 170/1002	S 168/1030	S 168/1034	S 169/1005	S 167/1001
Anatase				r						
Andalusite	r		r							
Apatite	r			r	r		5·5		r	r
Augite			r							
Biotite	1·0	r	6·8	r	r	r	r	r	r	21·2
Chlorite	r	r	10·4		r	r	r	r		r
Epidote	14·3	3·8		1·4	95·0	92·0	1·6	20·2	2·5	15·8
Garnet	r	r		3·4	r	r	r	r	r	r
Hornblende	63·1	36·3	r		r	r	r	54·8	1·5	53·6
Kyanite									r	4·8
Muscovite		r						r		r
Opaques	r	53·6	81·2	86·0	r	4·0	76·8	24·5	89·4	r
Rutile			r	r					2·1	
Sideroplesite				r						
Staurolite		?								r
Titanite	18·8	r	r	r			12·7		1·6	r
Topaz	r	r				?				r
Tourmaline		r		r	r	r	r		r	
Zircon	r	2·2	r	9·1	r	r	1·5	r	1·8	2·4
Zoisite	r	r		r	r					r

The beds are friable, unfossiliferous, yellow sandstones which are generally massive, although in places they show horizontal stratification. Associated with the sandstones are lenses of quartz gravels and thin discontinuous seams of lignitic coal. A detailed description of these beds has been given by Wood (1956).

The domination of the heavy mineral suite by members of the epidote group gives the sediments a unique character. Other non-opaque minerals contribute little to the constitution of the rocks, and all are rare in quantity. Among the epidotes there is a complete range of members from iron-rich pistacite in composite granular forms to clinozoisitic epidote and zoisite in tabular grains or as mantles on the ferriferous variety. The colourless clinozoisitic variety is most common; green pleochroic pistacite makes up only 18% of the total epidote content. Secondary outgrowths of iron-epidote and clinozoisitic material are seen as needles and stumpy columns. Of the other minerals that occur, blue-green hornblende appears in fibrous elongated grains with dentate ends, garnets in worn and pitted dodecahedra, and zircons, both anhedral and euhedral, are present within the same grade sizes. Stout prismatic crystals of three pleochroic varieties of tourmaline are also present: pink to brown or green, and more commonly brown to black.

Conclusions

The heavy mineral concentrates of the Gore Lignite Measures are remarkably similar to those recorded by Hutton and Turner (1936) for a fossiliferous Tertiary sandstone 26 miles to the north-west at Waikaia, southern Otago, the only apparent difference in mineral content being the presence of prisms of blue tourmaline in the Waikaia rocks. In the absence of complete data on the mineralogy of Southland and southern Otago, it is difficult to indicate an area of provenance for all the epidote minerals. The occurrence of granular forms, especially those with clinozoisitic mantles, suggests an affinity with the mineralogy of the Permian–Jurassic sediments, and this relationship is strengthened by the nature of the tourmaline and zircon. The absence of blue tourmaline as an indicator of detritus derived from the Otago schists points to a lack of sediment originating in that area of provenance, and the relative scarcity of schistose quartz fragments in the quartz-dominated light concetnrates supports this hypothesis. On the other hand, the tabular subidiomorphic grains of clinozoisite may represent material from the Chlorite 3 to 4 subzones of Hutton (1940).

Although a mineralogical correlation with the Waikaia sediments is indicated, an age assignation on this basis is purely tentative, as samples from the marine succession elsewhere in Southland have shown that identical heavy mineral assemblages occur at widely separated stratigraphic levels in the Tertiary rocks.

GENERAL CONCLUSIONS

The foregoing descriptions of heavy mineral assemblages from the Southland coal measures point to several conclusions of paleogeographic interest. There is no continuity of mineralogical characteristics from one set of coal measures to the next. This suggests that deposition of the sediments was essentially a local process, so that each area of provenance in existence at that time supplied detritus to a restricted distributed province, the boundaries of which were controlled by topographical barriers of high relief.

There is a relationship between the nature of the detritus and the geographical position of each coal measure basin with respect to three areas of distinctive older rocks—i.e., the Fiordland gneisses and intrusives, the Otago schists, and the Permian–Jurassic sedimentary rocks. As typical examples, the derivation of sediment for the following coal measures may be noted: those at Tuatapere are related to the Fiordland rocks; the Ohai measures are admixtures of varying amounts of older sedimentary material with debris from the Otago schists; and the Waimumu beds are almost exactly comparable in their heavy mineral content with nearby Permian–Jurassic sediments.

A base-levelled erosion plain of post-Jurassic but pre-Tertiary age in western Southland was described by Park (1921, p. 15) as the "Southland-Otago peneplain" which "became submerged by a slow positive transgression of the sea, and was covered with a relatively thin sheet of deltaic sediments" constituting the lower Tertiary coal measures. The same peneplain has been recognized by Benson (1935), Cotton (1938), and Macpherson (1946). Recent work, including the present study, indicates that subsequent to the peneplanation and prior to the deposition of Tertiary formations the peneplain was distorted and broken, so that basal sediments of the covering strata in large part were derived locally and deposited in isolated basins. A similar conclusion was reached by Hutton and Turner (1936), and by Lillie (1950, p. 334), who stated that, "Although the Mesozoic and older rocks were probably peneplained before the deposition of the Tertiary, it seems likely that considerable warping or faulting of the peneplained surface occurred in pre-Tertiary time". The textures and heavy mineral assemblages of the Tertiary rocks described here support this view. In none of the coal measure sediments is there any approach to effective sorting or rounding of the constituent grains. These rocks have the heterogeneous qualities of detritus that has originated locally and rapidly.

However, with marine transgression in post-coal measure time, there seems to be a much more even spread and greater mixing of materials derived from the three main source areas. Grab samples of post-coal measure marine beds have been taken from the following localities (Table 3):

(a) Whaingaroan (lower Oligocene) marine siltstone on the banks of Ohai Stream near Birchwood village (sample S 168/1030).

(b) Waitakian–Duntroonian (middle Oligocene) sandstone on the ridge south of Birchwood village (S 168/1034).

(c) Otaian–Hutchinsonian (upper Oligocene) limestone; quarry at Centre Bush, 21 miles south-east of Ohai (S 169/1005).

(d) Altonian (lower Miocene) sandstone from the north bank of Wairaki River, north of Clifden (S 167/1001).

Heavy concentrates from these rocks contain mineral mixtures unlike any others described from the coal measures. In all samples, epidote and sphene occur as detrital and derived authigenic grains. Tourmaline is absent in two samples, but in the other two ap pears in a large number of pleochroic varieties. Similar features about the distribution of hornblende, kyanite, and titanite indicate that sediment from the metamorphic terrains was being spread farther to the south and east than previously. The succession of heavy suites in the Ohai area is the best example of this change in mineralogy. Samples from near the base of the Ohai coal measures yield a rich and varied suite which, towards the top of the coal-bearing beds, becomes more simplified and approaches the composition of adjacent Mesozoic sediments. The succeeding Whaingaroan to Waitakian marine sediments contain a much higher proportion of metamorphic or acid igneous material.

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A SECTION OF ^{14}C ACTIVITIES OF SEA WATER BETWEEN 9° S AND 66° S IN THE SOUTH-WEST PACIFIC OCEAN

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Summary

Since late 1956 ^{14}C activities of 16 surface and 22 subsurface samples of sea water have been determined. The distribution of these activities in a section extending from 9° S to 66° S through the South West Pacific Ocean is described and compared with ideas of the nature and movements of water masses inferred from conventional oceanographic data.

It is confirmed that upwelling of Deep Water occurs in a divergence region near 64° S and that sinking occurs near the Antarctic Convergence at 61° S.

The upwelling water at the divergence has a low ^{14}C activity and water sinking at the convergence does so while the ^{14}C content is still far removed from equilibrium with that in the atmosphere. The activity of this sinking water is about 6% to 14% lower than that of water sinking near Greenland, so that great care must be taken in interpreting the activity of a sample as the time spent since leaving the surface, unless there is only one possible source of sinking water. However, if the distribution of ^{14}C activity is sufficiently well known, the maximum possible time or the least possible time since sinking may be estimated in certain circumstances.

Other features of the distribution allow interpretations that are tentative only, owing to the small number of observations within the section and the lack of data to the east and west, particularly in regions from which water masses move into the section. In most cases there is agreement with possible interpretations of the salinity and temperature distributions suggested by previous authors.

It is suggested that the use of the ^{14}C activity as an indicator characteristic may provide information in a very powerful manner in certain cases where the temperature and salinity characteristics vary only slightly, because of the requirement that density surfaces must usually be almost horizontal. In such cases nearby water masses near the same level may have widely different activities since, even though they originate from similar sources, they may have done so at greatly dissimilar times and have followed different paths. The activities in the Intermediate and Deep Waters north of New Zealand display this feature.

INTRODUCTION

During the last few years techniques of water sampling and analysis to determine the ^{14}C activity of sea water have been developed in laboratories throughout the world. ^{14}C activity is proportional to the ratio of the numbers of ^{14}C and ^{12}C atoms present in carbon available for exchange in sea water.

The concept of using the activity of the radioactive ^{14}C isotope as a tracer to determine the scales of residence times of carbon in the atmosphere, biosphere, and various ocean layers, and the rates of

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exchange between these "reservoirs" was evolved at an early stage of ^{14}C studies. Earlier writers have described the processes determining the presence and concentration of ^{14}C in these reservoirs (Libby, 1952; Craig, 1953, 1957; Suess, 1953, 1955; Cooper, 1956; Broecker, 1957; Rafter and Fergusson, 1957, 1958). Sampling of ocean waters has been aimed at providing quantitative estimates of the various rates of exchange between different ^{14}C reservoirs, and of the time that has elapsed since water at deeper levels sank from the surface. Some features relevant to such estimates are discussed in the present paper.

At the present stage of development of this ^{14}C technique it has become evident to the present writers that the ^{14}C activity may also be treated as a "characteristic" which may serve to help identify particular bodies of water and their motions, provided due regard is paid to time scales involved in the movements and to mixing processes. Accordingly, although all observations are not situated at the same longitude, the limited amount of data already at hand in the Western South Pacific is treated as a longitudinal section, and a preliminary consideration of the correspondence of the distribution of this new "characteristic" with existing notions concerning water masses, their extent, and their movements, is made. The data are yet far too few to allow estimates of dynamical quantities such as mixing coefficients to be made, however the efficacy of the ^{14}C activity as an indicator characteristic is amply illustrated in the present evaluation of existing data from the South West Pacific Ocean.

Previous observations of activity from the area considered here have been reported by Brodie and Burling (1958), Garner (1958a, 1958b), and Rafter and Fergusson (1958).

The General Movements of Water Masses Inferred From Existing Hydrological Data

From the analysis and interpretation of conventional oceanographic data certain deductions concerning the motions of the water masses sampled have been made by previous writers. Between New Zealand and about 64° S, westerly winds cause a general eastwards motion in water at all depths, and south of 64° S the mean winds are easterlies and there is a westwards drift of water to moderate depths. Since near-surface waters in the "Ekman" layer move to the left of the wind direction, there is upwelling near 64° S known as the Antarctic Divergence. Deacon (1937) shows from the distribution of temperature and salinity that Deep Water rises from considerable depths to the surface at this divergence. This upwelled water is cooled at the surface and fresh water added by melting, part then moving southwards and part northwards in the Ekman layers of the easterlies and westerlies respectively. The northwards-moving, cold and poorly saline Antarctic surface water meets warmer, lighter sub-Antarctic surface water farther north and tends to sink beneath it at the boundary known as the Antarctic Convergence. The cold Antarctic and warmer sub-Antarctic surface waters mix just north of the convergence and sink:

the mixed water then moves northwards to deeper levels along surfaces of almost equal density as the Antarctic Intermediate Current, which may be traced as a core of low salinity at levels between about 600 and 1500 metres or more as far northwards as the equator.

Sub-Antarctic water is present above the Intermediate Current, north of the Antarctic Convergence to a northern limit, the Sub-Tropical Convergence. North of the Sub-Tropical Convergence, warmer, much more saline Sub-Tropical water overlies the Intermediate Current. The Sub-Tropical Convergence lies in approximately 44° S off the east coast of New Zealand. West of New Zealand in the Southern Tasman Sea the sub-Antarctic surface water has temperatures about 3° C warmer, and salinities (34·4‰ to 34·8‰), about 0·35‰ higher than those in sub-Antarctic water to the east of New Zealand and in the eastern Atlantic. From the sections published by Deacon (1937) it would appear that these differences are due to the southward extension into sub-Antarctic regions above about 900 m, of warmer, more saline Indian Ocean water, and possibly to water from the southwards-moving East Australian Current. Sections published by Moroshkin (1958) support this view and indicate that the intrusion of Indian Ocean water occurs in the west of that Ocean. South of New Zealand lower salinity (< 34·4‰), colder water spreads northwards to reach 45° S to the east, and to lie near the convergence across the entire Pacific Ocean. However, a tongue of the warmer high salinity water extends round the edge of the Campbell Plateau south of New Zealand at depths between about 600 and 100 metres. The water movements west of New Zealand are not well known, but it is possible that the warmer, higher-salinity water in the sub-Antarctic region south of the Tasman Sea or a mixture of this with more northern water tends to move northwards up the west coast.

Sverdrup *et al.* (1942) show that a water mass exists in the Western Pacific north of the sub-tropical convergence and west of the longitude 160° W, which extends to the equator at the western limits, and to about 10° S near 160° W to 180° W. This Western Central South Pacific water mass (Sverdrup) at depths less than 600 to 700 metres above the Antarctic Intermediate Current has temperature-salinity (T-S) characteristics similar to the mean characteristics at the surface in August (winter) between 35° S and the Sub-Tropical Convergence. This suggests that the water mass is formed by water sinking from the surface in winter and moving northwards along surfaces of equal density.

Below the Intermediate Current is the Deep Water and below this is Bottom Water. The latter is formed by the sinking of modified Antarctic Surface Water which has moved southwards from the Antarctic Divergence. This becomes colder and more saline as freezing occurs in early winter over shallow continental shelf areas in the Weddell Sea and in some parts south of the Indian Ocean near the Antarctic Continent, to sink and spread northwards and eastwards near the bottom.

The Deep Water is formed largely by the cooling and sinking of saline Gulf Stream water near Greenland. This water moves southwards down the Atlantic between the Intermediate Current and Bottom Water, mixing with high salinity Mediterranean Sea water to join and move eastwards with the Antarctic Circumpolar Current system. Some of the Deep Water in this system moves upwards towards the surface at the Antarctic Divergence to become Antarctic Surface Water, the source of Bottom and Intermediate Water. Some may continue completely round the Antarctic continent, perhaps for several circuits, while a part moves north into the Pacific Ocean and perhaps (a matter of some controversy) into the Indian Ocean.

Stommel (1958) has suggested that below about 2000 metres there are strong currents northwards or southwards along the western edges of the major ocean basins. It appears that a small nett upwards motion throughout the major oceans is required to maintain the observed temperature distributions. If this upwards motion is assumed, and the downwards motion to great depths demanded by continuity is assumed to occur in the regions of Deep and Bottom Water formation, then a nett southwards motion of these waters must occur through most of the Atlantic Ocean and nett northwards motions into the Indian and Pacific Oceans. Because of the Coriolis forces resulting from movement on a rotating Earth, and their changes with latitude, such currents are concentrated on the western boundaries. In the Pacific Ocean this boundary lies roughly along the situations of the ^{14}C observations north of 35° S.

In the section (Fig. 2) samples were drawn from each of the water masses described above. It must be stressed that there is always mixing between adjacent water masses and that the boundaries between water masses are not all well defined, except possibly where there are pronounced thermoclines or haloclines.

The "Activity" of Sea Water

In this paper the results are discussed exclusively in terms of the observed enrichment of activity of each sample with respect to the activity of the New Zealand Wood Standard. No correction for fractionation has been applied, since measurements of the $^{13}C/^{12}C$ ratio (Craig, 1953, 1957), have been made on only a few of the samples. However, it is assumed that this correction is nearly constant for all samples and that the reported activities may be compared as a group. In the case of the observations for Station C.31 there was an unavoidable delay before processing, and some rusting of the containers occurred. Carbonates may have interacted with hydroxide ions and the accompanying fractionation may be significant. Mass-spectrographic analyses being made by members of the Institute of Nuclear Sciences should resolve this uncertainty, and, for the present purposes, the results for this station (C.31) are included in diagrammatic representations but they are not considered in the deductions drawn.

To compare the present results with those from other laboratories, allowance must be made for fractionation effects, which are due partly to natural fractionation (for example, at the air-sea interface and possibly through biological activity) and partly to processes occurring after the collection of the sample. Thus, a determination of the fractionation for each sample should desirably be made. Analyses are being made to check the post-collection effects, and future samples will be treated to inhibit possible biological processes.

For outside comparisons the level of activity of the New Zealand Wood Standard must be compared with that of standards used by other laboratories or with a suitable level such as that of wood prior to the "industrial effect". Suess (1953, 1955) first reported this effect which is due to the addition to the atmosphere of "old" carbon dioxide through the burning of fossil fuels and oil, in which the ^{14}C isotope is completely removed by decay. This has resulted in a general lowering of ^{14}C activity levels in the various carbon reservoirs: atmosphere, biosphere, and ocean. Fergusson (1958) has shown that the depletions of ^{14}C activity in the atmosphere and ocean up to 1953 are 2% and 1½% respectively, and that the New Zealand Wood Standard is depleted 1½%. Thus, — 1·5% must be added (increasing the depletion value) to the present figures to compare the activities with the level in "pre-industrial" wood.

Fergusson (1958) also estimates that the level of ^{14}C activity of ocean surface water stood about 1% above that of wood during the equilibrium states (Libby, 1952) existing prior to the industrial effect. This enrichment of 1% is due in part to isotopic fractionation, causing about 5% enrichment, this maximum value being offset by an amount determined by the rates of exchange of carbon between, and the relative amounts of exchangeable carbon in, the various carbon reservoirs. de Vries (1958) has shown that fluctuations of the order of 1% existed in the level of activity in the atmosphere over several centuries prior to the industrial effect. Fluctuations also occur with location. These variations are neglected in the present discussion.

Rafter and Fergusson (1957, 1958) have shown that during the past few years there has been an increment of the ^{14}C activity in the carbon reservoirs. This increase has been termed the "Atom Bomb effect", and is due to the interaction of nitrogen and neutrons arising from the explosions of nuclear weapons. This has produced enrichments above the 1954 levels of about 9% in the atmosphere and contemporary biosphere up to late 1957; there has been at least a doubling of this increment to the present date. The trend of activity in ocean surface water after November 1954 has been estimated by Rafter and Fergusson (1958) using values observed in water collected at Makara Beach west of Wellington in Cook Strait. Up to early 1958 there was apparently an increase in activity above that of November 1954 of about 2%. However, subsequent observations have shown that the observed increments rose to a maximum (about 2%) in late 1957, decreased to a minimum (about 1%) in late 1958, then rose to exceed 2% in July

1959. These observations are to be considered elsewhere by Mr G. J. Fergusson. Further comments regarding Makara Beach surface water are made later in the present discussion.

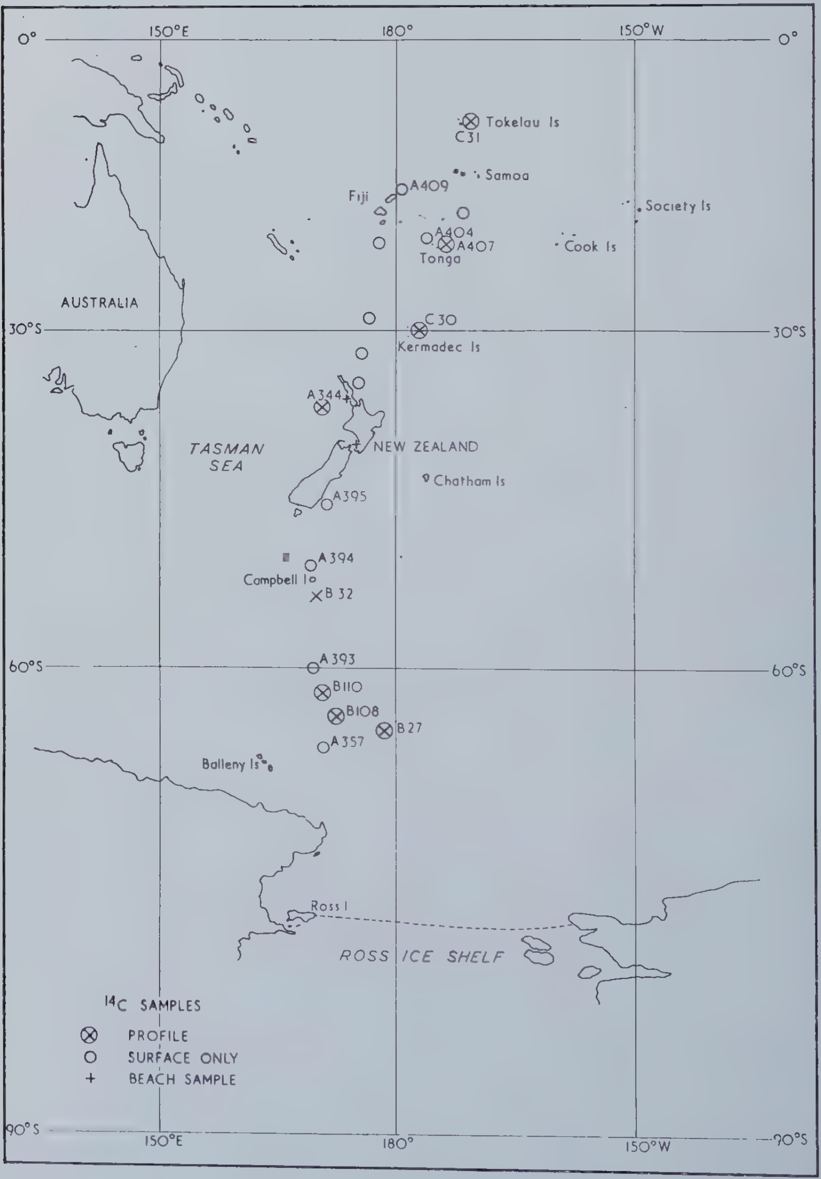

FIG. 1.—The positions of the observations—Stations C.30, A. 407, and C.31 lie almost along the axis of the Tonga-Kermadec Trench.

The Observations

Since December 1956 a series of large sea-water samples for the determination of ^{14}C activity has been collected by the N.Z. Oceanographic Institute using techniques described by Willis (1959). Positions of sampling are shown in Fig. 1, there being 6 profiles, each of 3 to 5 samples from various depths, 12 surface samples from different locations and 2 samples each from a single depth at two separate localities. Samples were stored on board ship in 44 gallon (200 litre) plastic-lined drums and returned for analysis by the Institute of Nuclear Sciences. The methods of extraction of CO_2 and of analysis have been described by Rafter (1955) and Rafter and Fergusson (1957, 1958).

The observed activities expressed in terms of the percentage enrichment with respect to the New Zealand Wood Standard, are given in Table 1, together with references, for results which have also been reported earlier. No correction has been applied to these values for possible fractionation.

Results quoted in Table 1, which have not previously been reported were obtained during the following two cruises. In September 1958 one of the authors (D.M.G.) and Mr R. P. Willis sailed on board H.M.N.Z.S. *Endeavour* from Auckland to the Pacific Islands north of New Zealand to work stations C.30 and C.31 and obtain other hydrological data. During November and December 1958, four members of the Institute, under the direction of one of the authors (R.W.B.) worked a series of oceanographic stations (including B.108 and B.110) between the Campbell Plateau and the ice-edge south of New Zealand from the frigate H.M.N.Z.S. *Kaniere*. Hydrological information from these cruises is in preparation for publication.

DISCUSSION

The "Age" of Sea Water

In the event that the basic assumption is correct, i.e. that the level of activity of water which has left the surface is altered only by the decay with time of the ^{14}C isotope and by mixing with nearby water masses, it is tempting, using the exponential decay constant for ^{14}C, to interpret the observed activity as a direct measure of the time since the sample left the surface, that is, as the "age" of the sea water. Such an age must be calculated from the activity with respect to the level of activity of the sample when leaving the surface; it is shown later in this paper that the levels are different at places at which sinking is known to occur.

Libby (1952) considered that the most likely way in which carbon may be removed from availability for exchange in the ocean reservoir is through the sinking to the bottom of dead organic material, which may spend many years in slow decomposition, but Libby points out that available evidence suggests that most of this material is dissolved

TABLE 1.—The Observed ^{14}C Activities Expressed as the Percentage Enrichment Relative to the ^{14}C Activity in the New Zealand Wood Standard.

N.Z.O.I. Stn. No.	N.Z.I.N.S. Lab. No.	Date	Lat. (° S)	Long. Depth (m)	Sample Depth (m)	Temp. (° C)	% Enrichment w.r.t. N.Z. Wood Standard		References	Sampling Method
B.27	R.222/1	28/12/56	64° 54′	178° 10′ E	2650	(0·0)	—24·7	±1·00	1, 2	A
B.32	R.222/2	1/1/57	53° 38′	169° 52′ E	750	6·5	—20·1	±1·00	1, 2	A
A.344	R.228/1	14/2/57	37° 25′	170° 35′ E	0	21·2	+1·01	±0·50	3, 2	Bucket
A.344	/2	15/2/57			100	16·1	—0·2	±0·45	3, 2	A
A.344	/3				300	12·6	—6·4	±0·35	3, 2	A
A.344	/4				850	6·1	—8·0	±0·38	3, 2	A
A.344	/5				1400	3·4	—16·1	±0·40	3, 2	A
A.516	/6	20/2/57	Muriwai Beach		0		—2·0	±0·40	2	Bucket
A.357	R.380	5/2/58	66° 29′	170° 55′ E	0	1·1	—6·26	±0·33	4, 2	F.M.
A.392	R.381	13/2/58	59° 56′	169° 38′ E	0	6·8	—2·29	±0·35	4, 2	F.M.
A.394	R.383	19/2/58	51° 31′	169° 07′ E	0	10·6	+0·02	±0·50	4, 2	F.M.
A.395	R.382	20/2/58	46° 13′	171° 12′ E	0	12·2	+0·97	±0·84	4, 2	F.M.
A.511	R.388/1	4/3/58	36° 35′	174° 52′ E	0	22·8	+2·10	±0·90	2	Pump
A.515	/21A	31/3/58	32° 56′	175° 48′ E	0	22·8	+2·50	±0·56	2	Pump
A.512	/3	6/3/58	28° 45′	176° 01′ E	0	22·0	+2·77	±0·60	2	Pump
A.513	/5	8/3/58	21° 17′	177° 29′ E	0	28·2	+2·91	±0·58	2	Pump
A.404	/10	18/3/58	20° 52′	175° 25′ W	0	26·6	+3·35	±0·86	2	Pump
A.514	/12	21/3/58	18° 18′	172° 21′ W	0	29·1	+2·70	±0·50	2	Pump
A.409	/15	23/3/58	15° 11′	179° 07′ W	0	29·7	+2·89	±0·55	2	Pump
A.407	/11	19-20/3/58	21° 21′	173° 16′ W	0	28·2	+3·33	±0·50	2	Pump
A.407	R.389/1				150	23·3	+1·80	±0·56	2	A
A.407	/2				580	9·0	—1·55	±0·56	2	A
A.407	/3				2500	2·0	—8·40	±0·70	2	A

C.30	R.479/4	8-11/9/58	29° 15′	177° 15′ W	550	(10)	−0·94	±0·50	A
C.30	/3	E. of Raoul Is.			1000	(5·5)	−2·27	±0·56	A
C.30	/2				2000	(2·5)	−12·25	±0·57	A
C.30	/1				3000	(1·5)	−9·96	±0·40	A
C.31	R.508/1	22/9/58	9° 05′	172° 00′ W	0	(30)	−1·0	±1·0	Bucket
C.31	/2	Near Tokelau Is.			200	(20)	+0·1	±0·60	A
C.31	/3				860	(5)	−7·6	±1·0	A
C.31	/4				3000	(1·5)	−13·1	±1·2	A
B.108	R.532/1	30/11/58	63° 43′	172° 24′ E	0	−1·6	−11·2	±0·50	F.M.
B.108	/2				100	−1·4	−9·8	±0·35	B
B.108	/3				200	0·9	−12·5	±0·60	B
B.108	/4				400	1·4	−11·9	±0·60	B
B.108	/5				1500	0·9	−14·1	±0·60	B
B.110	R.533/1	1-2/12/58	61° 56′	170° 32′ E	0	1·7	−8·4	±0·50	F.M.
B.110	/2				150	0·7	−14·4	±0·70	B
B.110	/3				500	2·3	−10·6	±0·60	B

Results published previously are indicated by numbers in the reference column.

1. Brodie and Burling (1958).
2. Rafter and Fergusson (1958).
3. Garner (1958a).
4. Garner (1958b).
5. Rafter (1955).

Thermometric or wire angle corrections have been applied to all sample depths.

"*In situ*" temperatures, obtained from accompanying hydrological data, are shown; except for stations B.27 (the temperature at a station 120 miles westwards and 60 miles northwards, 0·26° C at 2000 m, has been used), stations C.30 and C.31 (for which temperatures were interpolated from a section published by Sverdrup, *et al.* (1942); temperatures below the surface agreeing to 0·5° C with later observations in the vicinity).

The method of sampling is indicated in the last column.

F.M. refers to Fire Main.

A and B refer to the type of sampler described in Willis (1959).

during the settling process. Cooper (1956) suggests that such slow decay on the bottom would impart a fictitiously high age to the water. It is suggested here that although the relatively small proportion of carbon in the biosphere to that in the ocean ensures little effect through removal of carbon from the larger reservoir, the processes of transfer of organic carbon downwards from near surface layers to become available for exchange within a few years at moderate depths may be significant. The effect of mixing on activity and the possible effects of biological transfer processes on the distribution of activity will be the subjects of a later paper. For the present discussion it is assumed that all transfers are small except those caused by translations of mass or by turbulent mixing.

Since mixing occurs at all levels, the activity is an average over the activities of the very large number of individual "packets" of water contributing to the sample, and these "packets" may have travelled to the sampling situation via many different routes, and have spent different times since leaving the surface. However, if the mean translational processes, the nett input of ^{14}C and ^{12}C at a given place on the surface and the mixing processes (and possibly biological activities) have been in a steady state for a sufficient length of time, a steady state distribution of activities will have resulted.

It is evident that while the concept of "age" applied to a sample is not meaningless it has not always a straightforward application. For example, the derivation of a velocity from an observed activity and a known place of sinking with known activity, but with an assumed trajectory, will usually be greatly in error, except possibly for the setting of a lower limit. To obtain such a limit of the velocity we assume the shortest path L and must be certain that no mixing with higher activity, "younger" water can have occurred to lower the "age" and give a fictitiously high limit to the ratio L/age.

Limits to the "average age" of a sample can be set, when the activity at the time of sinking, the site of sinking, and the nature of the surrounding water are known. If the surrounding water is all "younger" and of higher activity, a lower limit can be derived. If the water surrounding the sample is all "older" and of lower activity except in the direction from which the sample has come, an upper "age" limit can be derived.

The ^{14}C Activity Section

The values of the observed activities are entered at the relevant depth and latitude in Fig. 2 and contours are drawn for enrichment intervals of 4% (the $+2\%$ and -2% contours are also shown).

As far as such contours reflect the average activity distribution we may consider the relation of the distribution today with the steady state distribution which has been assumed to hold prior to the industrial effect. Water sinking from the surface during 1950 and 1954 could, theoretically, cause, at any given position, a maximum decrease of

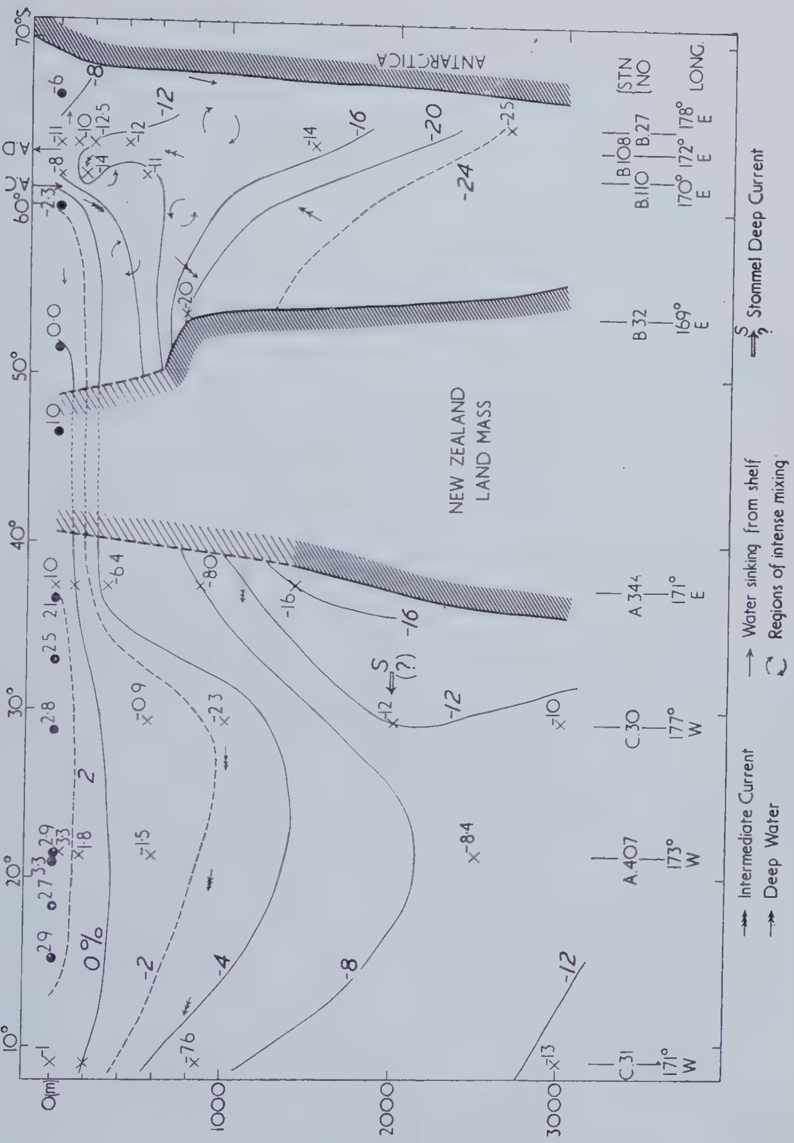

FIG. 2.—Section of observed ^{14}C activities—the values are percentage (%) enrichments w.r.t. to the N.Z. Wood Standard.

The Intermediate Current, identified by the core of low salinity—has been inferred by previous authors from conventional oceanographic data; the activity distribution is affected by other factors (see text).

Deep Water distribution is in accord with earlier theories in the Southern Ocean.

Sinking from shelf areas near the continent is suggested by the distribution of ^{14}C activity; (mixing prevents surface waters from reaching greatest depths to become Bottom Water).

Mixing between waters of Southern Ocean—inferred from the activity distribution; in general accord with earlier ideas.

Stommel deep current—the distribution of activity suggests that the current is within a thinner stratum at lesser depth than suggested by Stommel, and that it is composed of Intermediate Waters and Upper Deep Waters; however, east and west motions are possibly important.

activity of 1·5% below the values formerly holding at this position. In general the actual decreases at that position will be less, because of mixing and sinking at other times. The industrial effect would thus cause a slight upwards displacement of contours which would probably not be detectable for activities less than about −2% and would have a negligible effect in regions of active upwelling. The Atom Bomb Effect has raised the surface activities to slightly above the original steady state level and must cause a slight downwards displacement of contours at positions affected by water sinking since 1954. Again, these regions where there is upwards motion from deep levels will be least affected. The nett result from the two effects is not readily assessed; however, up to the present the displacements of contours must be very small, except in (a) the mixed surface layer at places where there is no divergence, and (b) beneath regions of active sinking.

Except in New Zealand latitudes there is fair east-west continuity in the characteristics of the water masses traversed; hence Fig. 2 should be generally representative of any north-south section through the Western Pacific containing the same water masses. Possible exceptions to this are noted below.

The most notable features of the section are the low activity level extending to the surface in circumpolar regions and the slope of lines of equal activity downwards towards the north and possibly rising towards the surface north of 20° S. In general the distribution points to low activities in the Deep Water, particularly in sub-Antarctic latitudes with low activity water reaching the surface near 63° S to 64° S; to maintain these low surface activities against the downwards transfer of ^{14}C from the atmosphere there must be upwelling at these latitudes.

Farther north, water with much higher activity extends downwards to between 2000 and 3000 m, and the general contouring suggests sinking and downwards mixing near and north of the New Zealand latitudes. At depths less than 700 m this downwards transfer may be by sinking from the surface near the sub-tropical convergence; at greater depths, however, there must be different east-west flows. These features will be discussed in succeeding paragraphs. The upwards trend in the extreme north suggests the presence of lower activity water farther northwards or of a general upwelling near the equator from quite great depths, but this hypothesis depends on the activities at Station C.31 whose unconfirmed values have been referred to earlier.

Surface Water Features

The observed surface water activities and temperatures are plotted against latitude in Fig. 3. The two lower curves in this diagram represent approximately the mean temperatures (right hand scale), during August and February, based on mean values given by Sverdrup *et al.* (1942). The positions of the Sub-Tropical Convergence (S.T.C.) offshore to the east of New Zealand, the Antarctic Convergence (A.C.), and Divergence (A. Div.) determined by recent surface and bathy-

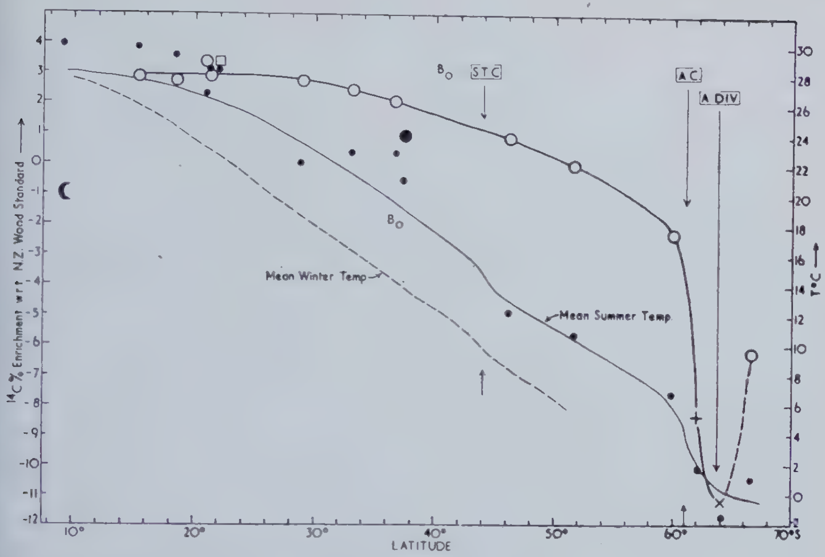

Fig. 3.—Observed surface water ^{14}C activities (symbols as in Fig. 4), and temperatures (small closed circles), plotted against latitude. The "curve of activity" is drawn through the mean of observed values north of 29° S and through all oceanic ^{14}C activities observed south of 29° S, except for station A.344. The curves for mean summer (February) and winter (August) temperatures (inferred from charts in Sverdrup, 1942) are drawn to agree with positions of the Sub-Tropical Convergence (S.T.C.), Antarctic Convergence (A.C.), and Antarctic Divergence (A. Div.) located during recent New Zealand Oceanographic Institute cruises. The symbol, Bo refers to the ^{14}C activity of samples from Muriwai Beach and from Makara Beach.

thermograph observations are shown in Figs 2 and 3. The mean temperature curves in Fig. 3 are drawn to correspond with these locations.

A smooth curve may be drawn in Fig. 3 to pass through the mean (+3%) of the observed enrichment values between latitudes 15° S and 23° S and through all other more southern values except that at Station A.344. The activity at Station C.31 at latitude 9° S (see section on the "activity" of sea water) lies well below the curve, there is, however, probably at the most only a small slope of the curve downwards north of latitude 15° S. Station A.344 lies to the west of New Zealand; the other surface activities were observed to the east or south of New Zealand a year later (those at 62° S and 64° S were observed 22 months later). The difference in time may explain part of the deviation of the surface ^{14}C activity at Station A.344 from the curve, however, it will be shown later that the difference could be due to location.

The decreased activity at the surface near the Antarctic Divergence is most pronounced, and the rise in activity just to the north and south reflects mainly the time spent at the surface by Antarctic surface water.

It is clear, however, that the extremely steep gradient across the Antarctic Convergence at 61° S must be due to the presence, in the sub-Antarctic region, of surface waters which have been affected by exchange of carbon with the atmosphere over a much longer period.

There is apparently no pronounced change in activity associated with crossing the Sub-Tropical Convergence, although the observations are as yet too few to state this with certainty.

The general decrease of both mean temperatures and salinity towards the south as far as the Antarctic Divergence indicates that an indicator diagram, similar to a T-S diagram, but in which the activities are plotted against temperature may be useful, and a T-Activity diagram has been constructed for all data (Fig. 4). The heavy curve representing the surface in this diagram has been drawn to pass through the observed surface water characteristics for ^{14}C activities less than 1%. All points observed south of the Sub-Tropical Convergence fall into this category. North of the Convergence the surface curve in Fig. 4 represents the mean of the observed activities together with the summer mean temperatures interpolated from the mean curves in Fig. 3.

All observations indicated by open circles were made during February and March 1958 (mid to late summer); the two points with lower ^{14}C activity (— 8·4% and — 11·2%) were observed about nine months later, before effective summer warming had occurred.

The general features associated with surface characteristics in the Southern Ocean stand out clearly with the Antarctic Convergence indicated by the sharp decrease in activity between — 2·3% and — 8·4% and the Divergence by the minimum activity, with an increasing surface activity farther southwards represented by the heavy dashed line. The higher temperature for the farthest south observation is simply due to the difference in the season of observation just described. If seasonal differences in activity occur near the Divergence, activity measurements would provide a means of assessing possible seasonal changes of upwelling.

The Sub-Tropical Convergence is represented in Fig. 4 by the slight bend at 12° C in the curve for surface activity north of the Antarctic Divergence. Since the change in salinity across the Sub-Tropical Convergence is very pronounced, it is expected that it will be prominent on an indicator diagram in which activities are plotted against the salinity, however, since final salinity values are not yet available for much of these data, this relation is not further considered here.

Two further activities measured from samples collected at two different beaches are shown in Fig. 3 (by the letter B) and in Fig. 4. These both differ significantly from the curves in both figures; suggested reasons are given in the section on the activity of Makara Beach water.

The Southern Ocean

Between latitudes 38° S and 62° S there is only one sub-surface observation (from 730 m on the southern slope of the Campbell

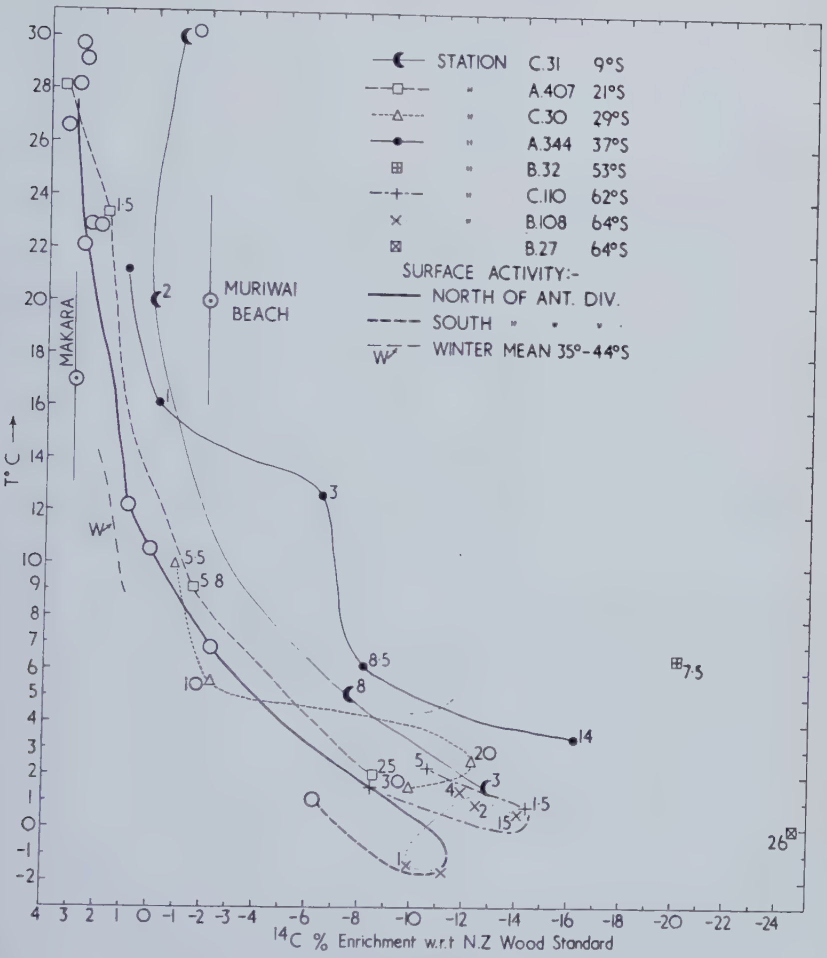

Fig. 4.—Indicator diagram of Temperature and Activity. The numbers refer to the depths of sub-surface samples in hundreds of metres.
A curve is drawn through the characteristics at each station. The curve representing the characteristics at the surface is drawn by interpolating values from the curves for ^{14}C activities and mean summer temperatures (see Fig. 3) for activities higher than + 1%, and temperatures above 12° C. For lower temperatures the curve is drawn through the observed characteristics.
The broken curve (marked W) represents surface characteristics in winter between latitudes 35° S and 45° S assuming that there is no seasonal change in ^{14}C activity. The data used are the observed surface activities (summer) and mean winter temperature as in Fig. 3.

Plateau). There can be no doubt, however, of the salient features of the contours drawn in Fig. 2.

Near the Divergence where the lowest observed surface water ^{14}C activity occurs (− 11·2%) there is a significant reversal below to

$-9{\cdot}8\%$ at 100 m. The observations (station B.108) were made within a large bay almost totally enclosed by thick pack-ice with more than 20 icebergs, some several miles long, within a distance of 50 miles, and at a time (30 November 1958) when melting was probably occurring quite rapidly. In this region the winter pack-ice usually extends 2° of latitude farther north to 62° S in August-September, but in February-March it retreats to about 68° S, i.e. to 4° farther south than the sampling position. Since freezing excludes carbon dioxide, it may be argued that pack-ice contains little or no absorbed CO_2, except perhaps a small amount entrapped by falling snow. Thus, melt water should contribute only a small increase in ^{14}C activity through the melting of the recent snows on the pack surface. If, however, there were an appreciable amount of CO_2 within "old" continental icebergs, etc., a decrease in ^{14}C activity due to melting of icebergs might occur. The formation of continental ice-cover by precipitation of snow enclosing CO_2, and subsequent compression, without melting and re-freezing, could well give rise to a significantly high CO_2 content. However, Midttun and Natvig (1957) showed that only about 1 part in 70 of the water moving northwards to cross the Antarctic Convergence is fresh water, the remainder being supplied by Deep Water. Hence the total carbon content contributed by precipitation or melting to Antarctic Surface Water is small, and it can not significantly affect the ^{14}C activity. For the observed significant reversal of activity at 100 m at Station B.108 a process of overturning is readily envisaged, caused either by local winds or by cooling.

This station was situated in comparatively shallow water, the depth changing from 700 m to 1900 m during the operation (it was impossible to assess accurately the drift direction since ice, water, and ship all drifted at the same rate and the sky was overcast soon after commencing, but by working back from sights obtained later, drift was apparently towards the south-east). Thus, some distortion of the contour lines near 64° S in Fig. 2 is possible due to topographical effects on the water movements. This depth is not shown in Fig. 2 at Station B.108, since Station B.27 is in much deeper water farther east near the same latitude.

The higher surface activity observed at Station A.357, 2° 46′ of latitude farther south and 1° 29′ of longitude to the west of Station B.108, 10 months earlier (5 February, 1958), may be due to a seasonal effect but is consistent with the southwards decrease of activity at deeper levels, and with conventional ideas concerning the surface water movements. That water down to depths of 2000 m or more in high latitudes may have a higher activity than the Deep Water farther north is readily explained if there is sinking over the continental shelf regions. The surface water south of the region of maximum upwelling has been assumed to have a mean southwards motion in the easterly-wind Ekman layer. If this is true the activity of this water, which depends mainly on the rate of exchange of $^{14}CO_2$ with the atmosphere, the thickness of the layer and the time spent since the water upwelled, should increase southwards. This is supported by the observed increase south of the divergence reported here. In the Weddell Sea and parts of the Indian Ocean bottom water is formed, but in other regions sinking perhaps takes place only to lesser levels. Cold water in the Ross Sea is sufficiently dense to sink to great depths. If this flows down the continental slope east of Cape Adare and follows a course similar to that of surface pack ice (Wordie, 1921; Deacon, 1937) which swings eastwards from the Ross Sea round Cape Adare, then this water could perhaps contribute to the observed conditions; this would not be prohibited by the bottom topography.

Perhaps the most startling results concern conditions near the Antarctic Convergence (near 61° S) near which surface layer waters must sink while still far removed from equilibrium with the atmospheric ^{14}C content; a point which is discussed later. The observed distribution strongly supports sinking in this region; to account for the sharp gradient of activity at the surface. Just north of the Divergence region it has been inferred from conventional observations that the surface layer transport is northwards and, as for the southern side; the ^{14}C activity should increase, with time and distance from the Divergence. This is consistent with observations.

The steep gradient of surface activity across the Antarctic Convergence shown in Fig. 3 may be slightly enhanced by the Atom Bomb Effect, since this has most effect on that water which has spent the longest time near the surface, and least influence on the newly upwelled water at the Divergence. Moreover, the additional ^{14}C increment due to the Atom Bomb Effect may decrease southwards if a meridional gradient in atmospheric ^{14}C activity exists.

The core of minimum salinity characterizing the Intermediate Water, slopes downwards to the north as shown by the arrows in Fig. 2 (to a deeper level than that of the observed activity of -20% at 53° S) and it is clear that there must be intense mixing across the isopleths to the north of the Convergence (Fig. 2). It is suggested that this may be largely due to a balance between the tendency of the Antarctic Surface water to sink along the density surfaces (negative buoyancy effect) and the upwards tendency at the bottom of the Ekman layer. This upwards tendency is due to the increase of westerly winds northwards from near 63° S to between 50° S and 55° S, in this longitude, causing a northward increase of Ekman layer transport; continuity imposing an upwards motion from beneath. From the Antarctic Convergence where the surfaces of equal density commence to slope steeply downwards, to several degrees of latitude northwards, the vertical stability is much smaller (the isopycnals are farther apart) than that south of the convergence. Thus, there is less opposition to both the sinking and rising tendencies, and there is a decided tendency for mixing to occur. That much mixing is observed to occur in this region has been remarked on by numerous authors (for example, Deacon, 1937).

The surface gradient of ^{14}C activity in the sub-Antarctic region (Fig. 3), from -2% close to the Antarctic Convergence to $+1\%$ near the

Sub-Tropical Convergence, suggests a northwards motion in the westerly wind Ekman layer. Deacon (1937) postulated such a motion with a return flow beneath; supported by the presence of a salinity maximum between the surface layer and the Intermediate current. Sverdrup (1933) suggested that the sub-Antarctic waters may move southwards due to greater cooling at the surface towards the south, the salinity difference being maintained by precipitation. The observed activity gradient superficially contradicts this latter theory since southwards surface movement would imply a constant or increasing activity in that direction. However, the possibility remains that the observed activity gradient could be maintained by mixing from below. The steep gradient across the Antarctic Convergence implies a southwards component of surface motion just north of the Convergence. Selected sampling in sub-Antarctic waters should provide an answer to this problem.

The downwards increase of activity at Station B.110 about 1° south of the Antarctic Convergence, between 150 m and 500 m is extremely interesting (Fig. 2). This may be a transient result of the mixing process referred to above, or it may indicate a nett relative transfer northwards at 150 m and southwards at 500 m. This would imply that the northwards Ekman layer transport extends to 150 m, which is almost at the bottom of the region of steep temperature gradient separating the cold Antarctic winter water from the warm upper stratum of Deep Water beneath. The deeper sample (from 500 m) was drawn from the core of this stratum and the lower activity suggests a southwards transfer of lower activity water at this depth, which must be due to mixing. Whether the observed reversal is permanent, or merely transient, it implies extremely intense mixing across the average isopycnals which slope downwards to the north, and implies also that higher activity water is mixed southwards beneath the surface layer. This appears to support Sverdrup's (1933) suggestion that the distribution of temperature in the upper stratum of Deep Water, which exhibits a southwards pointing warm tongue beneath the Antarctic surface water, is maintained by the mixing of Intermediate and Deep Water. Once again there are far too few observations to determine this point.

The mixing processes described above are indicated in Fig. 2 by the curved arrows. It would appear from this diagram that the low activity value at 700 m at Station B.32 implies a great admixture of Deep Water into the Intermediate Current. However, it is suggested in the following section that the high salinity tongue extending from the west round the southern edge of the plateau may influence this value.

The Tropical and Sub-Tropical Regions

Sverdrup's suggestion for the formation of the West Central Pacific Water mass by winter sinking of surface waters between 35° S and 45° S has been described in the section on water movements. The somewhat similar shape of isopleths in Fig. 2 to isotherms in a temperature section suggests that the temperature-activity (T-A) surface characteristics between 35° S and 45° S may be similar to those above about 700 m farther north.

It is suggested that if Sverdrup's ideas were correct, then, provided the water sinks and moves to northern positions within a few tens of years, a proper use of the T-A indicator diagram such as Fig. 4 will test the validity of the assumption that the ^{14}C activity acts as a conservative property of sea water (that is that biological processes are not important in changing or transferring activities). If the rates of sinking were known by other means the assumption involving time is not necessary since "ageing" may be allowed for. Even if much mixing is involved, for conservative properties, the expected relations would be unchanged. Such relations could also be useful in supplying information on the rate of change of activity in the surface layer due to the Atom Bomb Effect or, conversely, this effect, if known, may be used to estimate the time of sinking.

The broken curve marked W in Fig. 4 corresponds with the mean activity and winter temperature curves in Fig. 3. The only two observed points which may correspond with this curve are those at 550 m and 580 m at 29° S and 21° S respectively, and for these the temperatures are near that at the surface at the Sub-Tropical Convergence, while the activity is 2% to 2·5% less. The difference corresponds roughly with the increase in surface water activity due to the Atom Bomb Effect (Rafter and Fergusson, 1957, 1958) between 1954/5 and March 1958. Prior to 1954/5 surface ^{14}C activities were decreasing because of the industrial effect. The activity values for the two samples thus correspond to a time since sinking of about three years. The slightly greater time indicated by the greater difference for the more northern station is barely significant.

It is interesting that Deacon (1933) showed that Antarctic Intermediate Water in the Atlantic takes about 4½ years after sinking near 47° S to reach the equator, which corresponds to a velocity of nearly 2 miles per day. For the present case the northwards velocity of this Central water would be about 1 mile per day (3½ years to move through 20° of latitude). However, if water concerned sank at earlier dates than 1954/5 it could have the same activity; thus, this velocity estimate is a maximum.

The curve in Fig. 4 for Station A.344 shows that, to the west of the North Island the water mass characteristics are considerably different below 100 m from those expected in the Western South Pacific Central water mass. Down to this level the difference could be due to the earlier sampling date (Atom Bomb Effect) or general warming of water that has upwelled. Upwelling has been demonstrated in this region. Below this level the greater ages for water at a given temperature agree with the suggestion that there is a sub-Antarctic influence off the West Coast of New Zealand. This agrees qualitatively with the high activity observed at Station B.32 where there may be a more direct influence of sub-Antarctic water from the South Tasman Sea in a tongue round the plateau (see the section concerning water movements inferred from hydrological data). However, many more observations will be required in the Tasman Sea and other regions to clarify the point.

The northwards pointing tongue of lower activity (older) water near latitude 30° S (open arrow marked S(?) in Fig. 2) suggests that a significant northwards component of motion with respect to water above and below, occurs at depths between 1500 and 2500 metres. The station is above the Kermadec Trench and in the longitudes at which Stommel (1958) predicts a northwards component of motion below about 2000 m. The present observation appears to support the theory, and flow is apparently confined to a comparatively thin layer, suggesting that the Intermediate Current may effect much of the northwards transport necessitated by the Stommel theory. If so, it readily explains why this current extends so far northwards near the same levels—a flow which can be due only to continuity necessitated by some factor such as that suggested by Stommel. Such a flow would, however, be expected to produce a much more pronounced northward extension of the tongue of low activity water and the general distribution suggests a considerable influence of eastward or westward transfer. It is possible that stations C.30 and A.407 do not lie along the axis of a northwards current and that the station at 21° S latitude is representative of conditions to the east or west of the current.

"Apparent Age" and Re-circulation at Depth

The general features near the surface in Antarctic regions (Figs 2, 3) indicate several interesting considerations.

The ^{14}C activity of surface water in the Antarctic is much further removed from equilibrium with the atmosphere than that farther north; water sinking at the Antarctic Convergence and near the Antarctic Continent has a low activity. These low activities are extremely important in influencing the characteristics of the Intermediate and of the Bottom waters and by mixing between the various strata must influence strongly the ^{14}C activities of Deep and Sub-Antarctic waters.

If we assume that the southward gradient of activity in the atmosphere at heights from which effective downwards transfer occurs is less than that in ocean surface water, then the downwards rate of transfer of ^{14}C across the sea surface will be greater in the Antarctic Ocean than elsewhere. This deduction is valid, since rates of transfer are nearly inversely proportional to concentrations of ^{14}C at the surface. Hence, this higher rate of transfer of ^{14}C in the Antarctic Ocean requires to be taken into account in estimating the net rate of transfer from the atmosphere to the ocean.

A comparison of the levels of activity in North Atlantic surface water and pre-industrial wood measured at Lamont Geological Observatory (Broecker, 1957) with those for Makara Beach water and pre-industrial wood (Fergusson, 1958; Fergusson and Rafter, 1958) obtained by the New Zealand Institute of Nuclear Sciences, shows that water sinking near Greenland in 1956 had a ^{14}C activity of about $+2\%$ in the present units. The activity of water sinking near the Antarctic Convergence is between -4% and -12%. Thus, it is evident that great care must be exercised in applying ^{14}C activity directly to estimate the time spent since leaving the surface, and in attempting to assess mean rates of travel by assuming trajectories of water parcels to reach the point of observation. Observed isopleths in the Southern Ocean suggest that much re-cycling is possible throughout the oceans. On the largest scale, some of the water sinking near Greenland may have a course in Deep Water down the Atlantic to Circumpolar Waters where it may move round the Antarctic Continent perhaps several times, and may deviate into and return from the Indian, Pacific, and even Atlantic Oceans. Northwards transport may occur in the Bottom, Deep, Intermediate, or Stommel Currents and southwards transfer in the Deep Water Current, together with possible re-cycling in transit on a smaller scale.

It is noted, however, that the ^{14}C activity of water sinking at the Antarctic Convergence may be as low as about -12% and the deeper waters are surrounded (in the section) by water of higher activity. Thus, an "age" limit may be computed. In this consideration we must assume that the activities decrease in the direction of water movement which is, from other considerations, apparently mainly eastwards.

Acceptance of the above value (-12%) as the lowest ^{14}C activity for any sinking water implies a minimum activity difference of -13% for the water with -25% enrichment (Station B.27) and the least possible age of this water as 1100 years. This minimum time implies that any major climatological changes within the last several thousands of years will be affecting the present deep ocean characteristics.

If we assume that ^{14}C activities in the Southern Ocean for the entire circumpolar region are similar to those shown in the section of Fig. 2, it follows that both Intermediate Water and Bottom Water in the Atlantic Ocean will be older than the Deep Water. The average activity of Deep Water in the North Atlantic given by Broecker (1957) is about 6·5 ($\pm 1\%$) less than that of North Atlantic Surface Water. This value corresponds roughly to about -5% in terms of he ^{14}C % enrichments discussed in this paper—a value in excess of that of water sinking near the Antarctic Convergence and probably fairly near that of water sinking near the Antarctic Continent. The newly formed Bottom Water, however, moves northwards from the Weddell Sea beneath low activity water from the Pacific Ocean, before advancing northwards into lower latitudes; its average activity will be decreased by its being mixed with this water. Also, Deep Water rising to the surface in the Atlantic Ocean, to move northwards and sink at the Antarctic Convergence as Atlantic Intermediate Water, consists largely of Deep Water (low activity) from the Pacific. Thus, where waters above and below the Atlantic Deep Water have moved north to latitudes where no Deep Water of Pacific origin is present,there will be a maximum of ^{14}C activity in a vertical water column in the Atlantic Deep Water. The intensity of a minimum activity in the Intermediate Water and the difference between Deep and Bottom Water will decrease northwards because of mixing.

Broecker's observations at 4° S in the Atlantic support this suggestion; the activities in Intermediate and Bottom Water at 800 m and 4800 m being more than 2% and 4% respectively, less than that of Deep Water at 2800 m. If we compute "ages" of Atlantic waters from the activities with respect to that of pre-industrial North Atlantic surface water, whose activity was about 1·5% above that of 1955-6, we find "ages" of about 660,900, and 1050 years for the Deep, Intermediate, and Bottom Waters at latitude 4° S. If there were no mixing, the average age for North Atlantic Deep Water would be 660 years, but this is actually the maximum time (see earlier discussion) since sinking at some place in the North Atlantic. The other age assessments are not valid, because the ^{14}C activity of the sinking waters must have been much below that of North Atlantic Surface Water. Deacon's (1933) estimate of the time for Intermediate Water to move from 47° S to the Equator is 4½ years.

The Activity of Makara Beach Water

Rafter and Fergusson (1957, 1958) show how the activity of Makara Beach water has varied since 1954. Fluctuations on a general increase in activity have occurred during this time; the increase being due to the Atom Bomb Effect—these fluctuations were described earlier in the section on the "activity" of sea water.

All oceanic surface data relevant to the discussion of this section were observed during February/March 1958, when the ^{14}C activity of Makara water was about + 3% w.r.t. to the New Zealand Wood Standard. This activity is plotted in Fig. 3 at (41° S) and in Fig. 4 in which an assumed temperature is used with a generous allowance for error.

A further point is plotted in each figure, which represents water at Muriwai Beach near Auckland, where, from other considerations, upwelling is suspected to occur. The characteristics for this sample, — 2% enrichment, 37° S latitude and the assumed temperature 20° C, indicate that upwelling does occur. (The relation to the curve in Fig. 4 for station A.344, about 200 miles offshore, indicates a correspondence of this beach water with that near 150 m at the station.)

It is known that upwelling occurs intermittently about 60 miles across Western Cook Strait from the Makara Beach site. Tidal and other motions cause much mixing in this region, thus, if there is a deviation from average oceanic surface water, the characteristics should be expected to lie below the surface activity curve of Fig. 3 and to the right of that in Fig. 4. In each diagram, however, the observed activity is higher than the average for oceanic surface water at the given latitude or temperature.

Such higher activities could arise: (a) through a more efficient transfer of carbon dioxide from the atmosphere due to aeration during breaking, run up, and possibly percolation through aerated beach sand, or (b) through the addition, by run off, of fresh water whose activity is near the atmospheric level, even though the total CO_2 content in this water is much less, or (c) the presence of decaying organic matter from a local stream or more distant rivers. These processes are aided in changing the activity level through the mixed column by the quite shallow depths near the beach, and their effect is increased by the high level of atmospheric activity now existing due to the Atom Bomb Effect. A salinity as low as 28‰ has been measured in water from near the ^{14}C sampling site, thus the effect from a nearby stream may be appreciable. There is also evidence to suggest that there is some concentration of river outflows from the northern Cook Strait area into the region off Makara Beach.

Despite the small number of oceanic surface observations a quite smooth curve can be drawn through the activities plotted against latitude in Fig. 3 and all deviations from this curve may be explained by features expected from other oceanographic considerations.

The following conclusions are drawn:

(1) Makara Beach water has a rather higher activity than that of oceanic surface water offshore. This point may easily be checked.

(2) The increase of activity in Makara Beach water, despite the presence of fluctuations, will reflect the increase of activity in offshore surface water, which is the main source of water supply to the beach. Owing to the processes suggested above, however, the mean rate of increase of activity in the beach water may exceed that of offshore surface water, so long as the atmospheric activity continues to increase at the present rate.

(3) The observed fluctuations in the activity of Makara Beach water may be due to occasional upwelling in Western Cook Strait, to differences in the intensity and depth of mixing in nearby surface waters, or possibly to the presence offshore at different times of sub-Antarctic or sub-tropical water masses. These features are not necessarily independent. By choosing a further sampling position well offshore east of New Zealand and about 100 miles north of the fairly stable position of the Sub-Tropical Convergence it is hoped to avoid the first and last of these three influences.

CONCLUSIONS

The distribution of ^{14}C activity in the Southern Ocean is in general accord with inferences concerning water motions deduced from conventional data. Positive support is given to the existence of upwelling near 64° S at the Antarctic Divergence, and of sinking the Antarctic Convergence, and less strongly, of sinking near the Continent in the Ross Sea region.

The low ^{14}C activity of water sinking near the Antarctic Convergence (about 6% to 14% lower than of water sinking in the North Atlantic) shows that the concept of "age" must be considered with discretion. If we assume that the lowest ^{14}C activity of water sinking anywhere is — 12%, then the water at 2600 m at Station B.27 has been removed from the surface for at least 1100 years. However, from the following consideration, this would seem to be an underestimate. Only a small proportion of Intermediate Water mixes downwards; if a substantial amount mixed downwards, the salinity maximum in deep water would decrease eastwards. Unless activities lower than the — 6% observed at 66·5° S are found in sources of Bottom Water or in places where sinking to deeper levels occurs around the Continent it is, perhaps, more reasonable to consider this as the value for the lowest activity water contributing to the sample at B.27. With this consideration, the least difference between the activity of sinking water and the lowest activity observed is — 19%, which corresponds to a minimum age of about 1700 years. Some of the water making up the sample may have last been near the surface up to several thousands of years ago. Thus, it is probable that the ocean circulation is not in a steady state for time scales exceeding several hundreds of years; the consequences on the general circulation of the deep water and on the atmosphere particularly near the Antarctic Continent where the water upwells most rapidly may be important. Similar remarks have been made by Brodie and Burling (1958).

Inferences drawn from the distribution of ^{14}C activity in the northern part of the section are of a more tentative and less definite character; however, they are worth making at this early stage in the use of a new technique. Along the low salinity core of Intermediate Water to the north of New Zealand, indicated by arrows near 1000 m in Fig. 3, there is present water with markedly different activities. There is some indication that a northwards current over the Kermadec Trench similar to that postulated by Stommel (1958) exists, but at shallower depths that include the Intermediate Current. However, the presence of low activity water near 20° S, down to depths including the Deep Water suggests that north and south of about 25° to 30° S, Intermediate Water and Deep Water must have different motions. The observed distribution could not result from downwards mixing below about 700 m. If downwards mixing took place below this level the observed salinity minimum near 1000 m would be destroyed. Many more observations of a conventional oceanographic nature and of ^{14}C activities will be required before this question can be answered with any certainty.

There is a fairly uniform horizontal distribution of temperatures and salinities below about 700 m in this region, no doubt due to the relation of these properties to the density distribution. However, there is a strong suggestion in the case cited above that, despite this uniformity, the Deep Water and possibly Intermediate Water north of 30° S have had very different histories from the equivalent water masses south of this latitude. The differences may result from waters near the same levels sinking at different places or times, with various ^{14}C activities;

they may also have travelled different paths and mixed with water with different characteristics. If the influence of biological processes has been slight, the continued sampling over wide areas will provid information of vital importance and high sensitivity for discriminating between water masses of apparently almost similar types but whose past histories have differed.

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